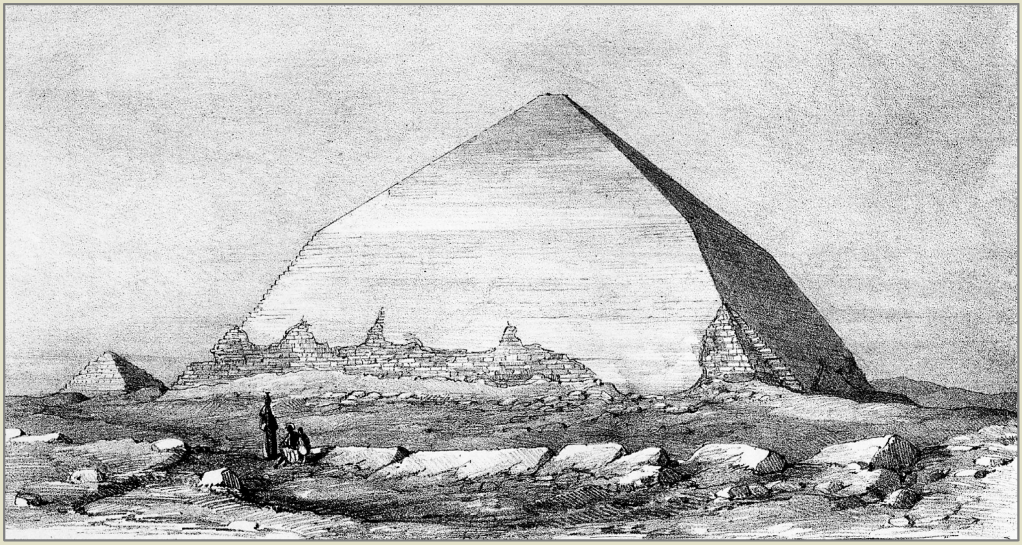
The Evolution of the Fourth Dynasty Pyramids

From an Engineer's Perspective

Hiroyuki Nagase



The Evolution of the Fourth Dynasty Pyramids: From an Engineer's Perspective

This book reexamines the major pyramid projects of ancient Egypt through the lens of structural development and the evolving technical decisions that shaped them. It challenges the familiar notion that the Fourth Dynasty pyramids represent a simple, linear march toward perfection. Instead, it argues that their history is defined by a far more intricate and irregular trajectory—one marked by experimentation, abrupt shifts, and pragmatic responses to failure.

Each pyramid embodies a distinct set of design choices, construction methods, and engineering challenges. Far from being isolated achievements, they form part of a dynamic sequence in which builders continually revised their assumptions, corrected earlier misjudgments, and adapted to unforeseen structural problems. What emerges is a non-linear pattern of evolution: a record of bold attempts, course corrections, and accumulated experience.

By focusing on design logic, construction technology, and the physical traces preserved in the masonry, this book examines well-known architectural features alongside long-standing "mysteries" rarely evaluated from a practical standpoint—most notably how the builders achieved the throughput required to produce, transport, and install 2.3 million blocks, and how the sustainability of such operations was maintained throughout the project. Hypotheses are tested, refined, and at times discarded as new evidence and structural insights emerge. It is written for readers interested in ancient engineering, construction history, and the technical interpretation of archaeological remains.

The discussion covers the pyramid sequence from Sneferu's Meidum, Bent, and Red Pyramids through the pyramids of Khufu, Djedefre, Khafre, and Menkaure, with additional consideration of Merer's Diary, Giza logistics, Dahshur, and the unfinished pyramid at Zawiyet el-Aryan.

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From an Engineer's Perspective

Hiroyuki Nagase

Tairiku Shokan
Yokohama, Japan

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Published by Tairiku Shokan, Yokohama, Japan

ISBN 978-4-911207-90-1

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PREFACE

For more than forty years, I worked at Panasonic in design engineering and project management. One lesson that experience taught me is that many so-called "successes" owe more to luck than to flawless planning, while failures—when examined carefully—reveal where the true problems lie. Yet even a long record of failures does not automatically lead to perfection.

My close study of the pyramids at Giza and Dahshur took place in August 2008. I had visited Giza once in the 1990s, but this was my first opportunity to examine the sites in detail. When I stood before the Bent Pyramid at Dahshur, I was struck by how clearly it displays the traces of extreme design change. The evidence of an initial flawed concept, the builders' struggle to cope with it, and their desperate attempts to prevent collapse were all unmistakable. As a project manager, I found this profoundly moving.

As I continued reading the works of Petrie, Vyse and Perring, Maragioglio and Rinaldi, and Dr. Mark Lehner, the mysteries surrounding the evolution of the Fourth Dynasty pyramids only deepened. What ultimately prompted me to write this book was the realization that monuments such as the pyramid at Meidum or the pyramid of King Djedefre—now little more than ruins—must have stood in far more complete form 4,500 years ago. I came to believe that these earlier pyramids existed before later kings and engineers as real, imposing structures, and that their appearance exerted a strong influence on subsequent design decisions.

This book is structured in two parts. The first examines how the

pyramids were actually built. Although the subject may appear "textbook-like," pursuing technically realistic solutions to the problems of mass-producing, transporting, and setting the roughly 2.3 million blocks of Khufu's pyramid led to conclusions that differ markedly from conventional explanations and popular accounts.

The second part explores the seemingly abrupt and contradictory changes observed in the Fourth Dynasty pyramid sequence. Here I present several ideas—perhaps closer to informed conjectures than formal hypotheses. These include the possibility that Khufu's subterranean chamber was originally intended as a burial chamber but later repurposed as an observation post; that Khufu's pyramid may not have been completed before his death; and that the entrance of Khafre's pyramid may have collapsed during his reign.

I do not offer these ideas to provoke controversy. Having passed the age of seventy, I simply wished to record the thoughts I have carried for many years. If this book encourages more rigorous, engineering-based approaches to pyramid studies—and if arguments more compelling than my own emerge—I would welcome that outcome. Above all, I hope this work serves as a starting point for readers' own reflections.

From a project-management perspective, the development of the Fourth Dynasty pyramids was anything but linear. Management methods and design philosophies shifted dramatically, and progress was far from smooth. As a project, the pyramid sequence cannot be called a perfect success. Yet these immense structures—still standing after 4,500 years and now among the most iconic monuments in the world—remain extraordinary achievements. Their enduring presence, I believe, is the greatest legacy of the pyramid-building enterprise.

Hiroyuki Nagase
July 2026

Part I

How Were the Pyramids Built?

CHAPTER 1

Examining the Materials Available in Ancient Egypt

The most fundamental constraint in any manufacturing process is the availability of materials. Even in modern industry, no product can be made unless the necessary materials and components can be obtained. The next essential factor is the method of fabrication: without a workable method, production cannot proceed. Because this book concerns the construction of pyramids, the physical materials and the techniques used to manipulate them form the foundation of the entire discussion. Like modern engineers, the ancient Egyptians began by securing the materials on which their construction processes would depend.

Let us therefore examine the materials required for pyramid construction.

1. Stone

Stone was by far the most extensively used material in pyramid building, and understanding its properties is essential to understanding the construction process as a whole.

It is generally thought that one of the principal reasons Giza was selected as the site for pyramid construction was that the core masonry—used in the greatest quantities—could be quarried locally. South of Khufu's pyramid, the depression known as the Central Quarry remains as evidence of this activity, and the Sphinx itself is believed to have been carved by reshaping the remnants of another quarry.

The fine limestone used for the outer casing stones—second only to core blocks in total volume—was quarried at Tura, located approximately

Table 1-1. Principal Stones and Their Uses in Pyramid Construction

Rock Type	Primary Use	Main Source	Distance from Giza
Limestone	Core masonry	Giza Plateau	0–2 km (local)
Fine Limestone (Tura)	Casing stones	Tura, east bank of the Nile	10–15 km southeast of Giza
Granite	Burial chamber and special spaces	Aswan	1,000 km upriver (following Nile bends)
Diorite	Tools	North of Fayum	50–100 km southwest

10–15 km upstream on the opposite bank of the Nile. Tura remains an active limestone quarry even today and hosts cement factories that use its limestone as raw material.

Other essential materials included gypsum, used as the primary ingredient in mortar, sourced from the northern Fayum region about 40 km southwest of Giza. Quartz sand for polishing could be collected in Giza.

2. Metals

In the Old Kingdom, the Egyptians relied almost exclusively on copper for tools, weapons, and construction equipment. Iron smelting was not yet known, and Egypt produced virtually no tin, making bronze production impossible. Without iron, brass was also unknown.

Egyptian copper ore naturally contained arsenic, producing an arsenical copper that was somewhat harder than modern pure copper, though still limited in strength. By the Old Kingdom, copper mining was well developed, and copper was not a rare metal. However, it was seldom used structurally; its primary role was in tools.

Table 1-2. Comparison of Copper Use in Ancient Civilizations

Region	Copper Ore	Tin	Fuel	Bronze Production
Egypt	Copper + arsenic	None	Scarce timber	Impossible
China	Copper naturally mixed with tin	Available	Abundant forests	Bronze produced
Mesopotamia	High-purity copper	Tin nearby	Forests available	Deliberate alloying

Copper tools were adequate for cutting limestone but insufficient for working granite. As a result, granite had to be shaped using alternative methods such as pounding and sand abrasion. The absence of bronze and iron also imposed practical limitations: nails, levers, and other metal fittings common in later civilizations were unavailable.

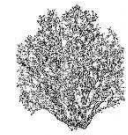
3. Wood

Because most of Egypt's territory is desert except for the banks of the Nile and the Mediterranean coast, the country was never rich in timber resources. The arid climate prevented coniferous trees from growing, and large straight trunks—essential for structural use—had to be imported, most notably the cedar of Lebanon.

The Nile Valley was the principal source of native Egyptian wood, but trees could not grow in the floodplain itself because annual inundations repeatedly destroyed vegetation. As a result, native trees were limited to the narrow areas of river terraces and other elevated ground.

Among Egypt's native species, acacia was the most important hard and durable wood. However, unlike conifers, acacia does not grow into tall, straight trunks, and its use was therefore restricted to small components.

Table 1-3. Principal Woods Used in Ancient Egypt

Cedar of Lebanon	Acacia	Sycamore fig	Tamarisk	Date palm
				
Long, light, strong, easy to work	Hard, durable	Soft, workable, wide boards	Dense, fine-grained	Poor for carpentry
Ships, beams, high-quality construction	Small boats, furniture, coffins	Furniture, coffins, construction	Beams, coffins, tool handles	Low-grade uses
Imported, valuable	Does not grow large	Fruit edible	Short lengths	Abundant, fruit edible

Sycamore fig, a species of Ficus, was widely cultivated both for its edible fruit and for timber. It grows rapidly and, unusually for native Egyptian wood, can yield planks 30–50 cm wide, with exceptional pieces reaching about 60 cm. For this reason, it was extensively used for furniture, coffins, and the bottom planks of boats. Its wood, however, is relatively soft and therefore unsuitable for structural applications.

By contrast, the date palm—abundant in Egypt both as a wild species and as a cultivated crop for dates—grows into tall trees. Yet its internal fiber structure differs fundamentally from that of typical hardwoods and softwoods, making it impossible to plane or cut with precision. As a result, it was considered a poor-quality timber with limited applications. Nevertheless, because date palm wood is strong in compression, it may have been suitable for use as rollers in stone transport.

Importantly, Egypt had no large bamboo, unlike Asia. Thus, the

Fig. 1-1. Papyrus (photographed in the front courtyard of the Cairo Museum, 2008. Unless otherwise noted, all photos in this book were taken by the author.)

bamboo scaffolding common in Hong Kong or Southeast Asia would have been impossible in ancient Egypt.

Although not a wood, papyrus was an important plant material. A perennial reed, it grew rapidly during the Nile's inundation, reaching heights of 3–4 meters. The pith was used to make papyrus sheets, while the outer rind was used for rope and sandals. Because the pith contains air, papyrus bundles had high buoyancy and were used to make boats. However, papyrus boats deteriorated quickly when left in water, and their usable lifespan appears to have been short—likely on the order of several months.

4. Ropes

Ropes were not primary building materials, but they played a crucial supporting role in construction—particularly in transporting heavy stones, securing scaffolding, and performing lifting operations. In tasks

that required pulling or raising massive blocks, ropes were indispensable.

In ancient Egypt, ropes were made from papyrus, flax, and fibers extracted from the cores of date palms. By contrast, ancient China relied on hemp, which produced exceptionally strong ropes, while Mesopotamia used wool, goat hair, and palm fibers. Each civilization developed rope-making traditions shaped by the materials available in its environment.

Egypt, however, had little access to hemp. As a result, Egyptian ropes were made from relatively short fibers, giving them low tensile strength, high elasticity, and a tendency to fray or break. Their durability was also limited. From an engineering standpoint, Egyptian ropes were weak materials—far inferior to the hemp-based ropes familiar in other ancient cultures.

Modern readers often imagine rope as a strong and reliable material because Manila hemp rope—long-fibered and extremely durable—was widely used until recently, including for mooring large ships. This modern image can be misleading. Egyptian ropes were fundamentally different in both quality and performance.

Tensile strength is typically expressed in daN (decanewtons), where 1 daN corresponds to roughly 1 kg of vertical load. Modern Manila hemp rope with a diameter of 10 mm has a breaking strength of 670–800 daN, and because strength increases with the square of the diameter, a 20 mm Manila rope reaches 2,600–3,250 daN.

These values correspond to typical manufacturer specifications and internationally recognized rope standards, which consistently report similar strength ranges for natural-fiber ropes.

Other natural fibers are weaker. Jute rope of 10 mm diameter has a breaking strength of 300–600 daN, and cotton rope 300–500 daN—roughly half that of Manila hemp.

Given the short fibers of papyrus and flax, and the low tensile strength of date-palm fibers, Egyptian ropes likely performed at the lowest end of the jute/cotton range: approximately 300 daN for 10 mm and 1,200 daN for 20 mm.

However, rope must be evaluated not only by breaking strength but also by safety factor. Even in modern industrial standards, rope is rated by both its ultimate strength and the safety factor required for practical use. Manila hemp, with its long, strong fibers, typically uses a safety factor of 1/7 to 1/5. Jute and cotton may require 1/10.

For ancient Egyptian ropes—made from short, inconsistent fibers and produced without strict quality control—a conservative safety factor of 1/15 is appropriate.

Under this assumption, a 20 mm Egyptian rope would have a working load of only 80 daN. Even if one were willing to accept a risky safety factor, the working load would be no more than 200 daN. In practical terms, this means that even with a 20 mm rope, pulling a 200 kg stone would already be approaching the limit of safety.

For comparison, a modern 20 mm nylon rope has a breaking strength of 7,200 daN and a working load of about 1,200 daN. Comparing working loads, the Egyptian rope's 80 daN was therefore only about 6.7% of that of modern nylon rope.

Given that even relatively small casing stones weigh over one ton, and core blocks can reach six tons, it becomes clear that hauling large stones

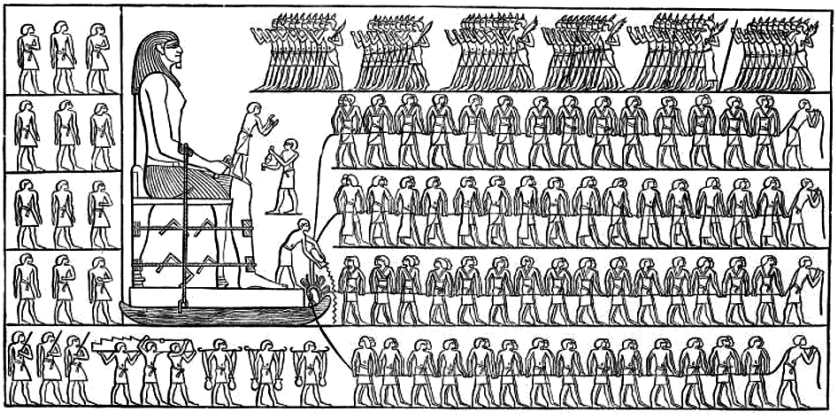


Fig. 1-2. "Transport of a colossus, from a tomb at El Bersheh" The Miriam and Ira D. Wallach Division of Art, Prints and Photographs: Picture Collection, The New York Public Library. The New York Public Library Digital Collections. 1881-1882.

up steep ramps using long, thick ropes—like a giant tug-of-war—would have been highly impractical. Likewise, lifting stones with pulley systems would have been extremely limited, not only because of weak ropes but also because Egypt lacked strong, long timber suitable for constructing robust scaffolding.

A frequently cited counterexample is the famous relief from the tomb of Tehutihetep at el-Bersheh, which shows a colossal statue being hauled on a sledge by a large number of men. This image is so striking that it has shaped the modern imagination of how the Egyptians transported heavy objects.

However, the relief invites a more nuanced interpretation.

The scene shows four ropes, each pulled by a separate row of workers. The number of workers appears exaggerated, but the arrangement raises an important question: why four rows?

Rather than imagining a stop-and-start motion—pulling, stopping, pulling again—it is plausible that the workers used a synchronized, alternating pulling technique.

Static friction requires the greatest force to overcome. Once an object is moving, kinetic friction is lower, and maintaining motion requires less force. If two rows pulled while the other two prepared, and then they alternated without allowing the sledge to stop, the workers could keep the statue moving using only kinetic friction.

This method would compensate for the weakness of Egyptian ropes.

Another notable feature of the relief is that none of the workers adopt a "tug-of-war" posture. No one is leaning back or bracing with body weight. Instead, they appear calm, pulling steadily and uniformly. This supports the idea that they were maintaining a constant, moderate speed—consistent with a technique designed to avoid static friction.

5. Mudbrick

Mudbrick is one of the most common materials encountered at Egyptian archaeological sites—arguably even more ubiquitous than stone.

Fig. 1-3. Mudbricks stacked in a retaining wall along a passageway (photographed in Luxor, 2008)

In domestic architecture, walls built of stone or timber were rare; most ordinary houses were constructed almost entirely of mudbrick. In ancient Egypt, mudbrick was the most basic and most versatile building material.

The raw material for mudbrick was the alluvial silt deposited annually by the Nile. After the inundation receded, a thick layer of fresh silt covered the floodplain between the Nile and the Giza Plateau. Over centuries, these deposits accumulated into deep, abundant layers, providing an effectively inexhaustible supply of material for brickmaking.

Mudbricks were not fired. They were made by mixing Nile silt with chopped straw, packing the mixture into wooden molds, removing the bricks from the molds, and leaving them to dry in the sun. Straw served two important functions: it prevented shrinkage cracks during drying by binding the clay matrix, and it helped the brick retain its shape even if minor cracking occurred.

Brickmaking took place on the flat ground exposed after the floodwaters receded. Because rainfall was extremely rare, bricks could be produced almost continuously for the seven months until the next

inundation.

Assuming a standard brick size of 30 × 15 × 10 cm, each brick has a volume of 0.0045 m^3. The production process was simple, and a single worker could easily make 100 bricks per day. Because the work required little skill and was not excessively strenuous, people of all ages and genders could participate. With 1,000 workers, daily output would reach 100,000 bricks, and over seven months, 21 million bricks—a total volume of 94,500 m^3.

For comparison, the volume of Menkaure's pyramid at Giza is estimated at 235,000 m^3. (This estimate follows the value given by Mark Lehner in The Complete Pyramids, 1997.) Thus, in a single year, the volume of mudbrick produced could reach roughly 40% of the volume of a major pyramid.

Although unfired mudbrick is brittle under impact and easily broken, it has high compressive strength and is fully adequate for pavements and walls. The large mounds of surviving mudbrick debris at many sites demonstrate that, in Egypt's arid climate, mudbrick structures could endure for millennia. However, mudbrick deteriorates rapidly when exposed to rain or water, returning quickly to mud. It was therefore a material uniquely suited to Egypt's dry environment.

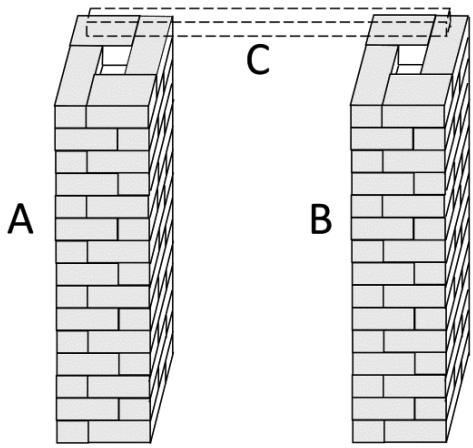


Fig. 1-4. Scaffold constructed by stacking mudbricks in a looped arrangement.

In modern construction, scaffolding is typically made from steel pipes or timber. In ancient Egypt, however, long, high-quality timber was scarce. For this reason, I believe that mudbrick was frequently used to build robust temporary scaffolding. A small team of workers could easily stack bricks into walls several meters high. Mudbrick walls are strong under vertical load but weak against lateral impact, which means they could be dismantled quickly when no longer needed.

For example, Fig. 1-4 illustrates a simple scaffold built by arranging four mudbricks in a loop to form one course, then stacking 15 courses to create a square pillar 1.5 meters high. A wooden beam (C) could be placed across the top. Each pillar (A and B) would require 60 bricks. For temporary use, mortar was unnecessary; the bricks could simply be stacked. A small crew could construct such a scaffold in half a day.

Attempting to build scaffolding from timber would have been far more difficult. Without pipe joints or clamps, wooden scaffolds would require complex joinery, diagonal bracing, and rope lashings. Compared with this, mudbrick offered a faster, simpler, and more stable solution.

In ancient Egypt, therefore, mudbrick was not only a fundamental building material but also an exceptionally practical material for temporary scaffolding.

For reference, I include here a wall painting from the New Kingdom, found in the tomb of Rekhmire at Luxor, which depicts the manufacture of sun-dried mudbricks. The sequence shows workers collecting mud

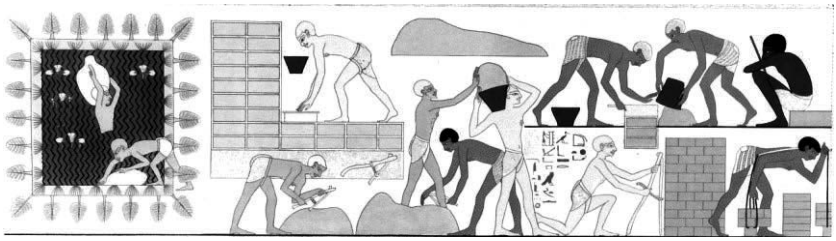


Fig. 1-5. A mural depicting the manufacturing process of sun-dried bricks. (Karl Richard Lepsius, Denkmäler aus Aegypten und Aethiopien, 1849–1859, Abth. III, Bl. 40. Public Domain Mark 1.0 via Internet Archive.)

from a pool, kneading it, placing it into molds, leaving the bricks to dry, and finally transporting the finished products. One particularly interesting feature of this scene is the dark-skinned figure seated at the far right, observing the work. This figure is generally interpreted as a Nubian overseer. However, such Nubian overseers would not have been common in the Old Kingdom.

I also find myself questioning whether the scene of workers scooping mud directly from a pool reflects actual practice. It seems possible that the painter was not reproducing a literal landscape but rather depicting an imagined or conventionalized setting.

CHAPTER 2

Considering Realistic Construction Methods

When modern readers imagine stone cutting, transport, and other work on ancient Egyptian construction sites, they often picture harsh, exhausting labor in which most tasks depended heavily on human muscle power. It is true that, in an age without engines, any work performed against gravity ultimately relied on human effort. However, it is difficult to imagine that pyramid construction consisted of unrelenting, brutal labor comparable to slave work.

According to widely accepted scholarship, the most intensive phase of pyramid construction coincided with the Nile inundation, when agricultural fields were submerged and farmers could not cultivate their land. These farmers were conscripted as laborers. If the work had been excessively harsh, it is unlikely that conscription would have proceeded smoothly year after year. Moreover, agricultural production—and the taxes levied upon it—formed the economic foundation of the state. Overworking farmers would have risked serious social and economic consequences.

This conclusion is not based on modern humanitarian values but on a colder, more rational assessment of what would have been sustainable. It is reasonable to assume that the labor demanded of conscripted farmers was kept within the bounds of what they were accustomed to during agricultural work. They were not treated as expendable.

Another key theme of this book is sustainability. Pyramid construction spanned more than a decade—twenty-seven years in the case of Khufu's pyramid. Any proposed method must therefore be evaluated in terms of whether it could be sustained over such a long

period.

Khufu's pyramid is estimated to contain approximately 2.3 million stone blocks. Even in modern mass production, such a quantity is extraordinary. For comparison, Toyota—the world's largest automobile manufacturer—produced about 11.3 million vehicles worldwide in 2025. Pyramid construction, therefore, must be understood as a project involving the mass production of stone blocks and the execution of a large-scale construction process. In this context, sustainability becomes an essential criterion.

Another important perspective when considering ancient Egyptian construction techniques is feasibility.

Although ancient Egypt was a highly advanced civilization, it faced severe constraints in construction materials.

Timber. Large, strong, flexible beams were virtually nonexistent along the Nile. Imported cedar from Lebanon was valuable and could not be consumed in large quantities on construction sites. As a result, long beams, robust scaffolding, and precise wooden shafts were structurally difficult to achieve.

Metal fasteners. Copper nails were too soft to provide the holding power of iron. Ropes could be used to lash wooden members together, but Egyptian ropes—made from papyrus, flax, or date-palm fibers—were weak and wore out quickly, making them unreliable as structural connectors.

Wheeled carts. Although wheels may have been known earlier, Old Kingdom axles lacked bearings, and friction would have increased dramatically under heavy loads. Suitable axle timber would also have been difficult to obtain. While carts may have existed, they were not viable for transporting multi-ton stone blocks.

Pulleys. Egyptians certainly used simple methods such as looping a rope over a log to change direction, but the modern concept of a pulley with a rotating wheel and axle—let alone compound pulleys—was unlikely to have been widespread. The durability of Egyptian rope was insufficient to support such lifting systems.

Levers. Without iron reinforcement, the tips of wooden levers would have been prone to breakage, restricting their usefulness in handling heavy stone.

Given these material constraints, modern assumptions about levers, pulleys, scaffolding, and carts cannot be applied directly to ancient Egypt. Any method that relies on such equipment must be evaluated with caution.

1. Process Design and Construction Infrastructure

In 2013, a team led by the French Egyptologist Pierre Tallet discovered a papyrus archive—now known as the Diary of Merer—at an ancient harbor site on the Red Sea coast. Tallet has stated that Khufu reigned for 27 years, a figure introduced in the Conclusions of his 2017 edition of the diary.

The basis for this figure has not been clearly disclosed (see Chapter 4, Section 4, and Column 4 for further discussion). Nevertheless, among the various reign-length estimates proposed in recent scholarship, 27 years is the longest. A longer reign spreads the same 2.3 million blocks over more years, which lowers the average annual and daily production rate required. I therefore adopt 27 years here not because I regard it as established, but because it yields the most conservative possible baseline: whatever the true reign length turns out to be, the actual pace of construction can only have been faster than the figure calculated below, never slower.

If we assume a 27-year construction period on this basis, the average annual production would be 85,185 blocks, or 233 blocks per day.

However, as discussed in later chapters, the number of blocks required per course decreases as the pyramid rises, while the available working area also shrinks, forcing a reduction in the number of workers who can operate simultaneously. For this reason, production cannot be treated as uniform across the entire construction period. During the early and middle phases of construction, it is likely that a daily output of

Fig. 2-1. Comparison of block size in Khufu's pyramid with a human figure.

approximately 500 blocks was required, even under conservative assumptions.

Because the main construction season coincided with the Nile inundation—summer—daylight hours were long. Excluding meals and rest, workers may have had up to 11 hours of productive time per day. Even so, producing 500 blocks per day requires completing one block every 1.3 minutes. The more one considers this, the clearer it becomes that this was not merely "construction work" but a large-scale industrial production system requiring careful process design and continuous throughput.

The production of stone blocks can be broadly divided into two major stages: "quarrying" and "shaping."

From the nature of the work, quarrying was likely carried out by teams of workers who moved laterally across the rock face, cutting out one block after another. I assume that each sub-process—preparing the quarry surface, cutting the grooves, inducing the final fracture, and removing the block—was assigned to a dedicated group of workers, and that these units advanced sequentially to the next target area.

By contrast, the processes following quarrying were, conceptually, a kind of flow production. After rough shaping came intermediate finishing, final finishing, and—in the case of casing stones—precision finishing. Because the blocks were large and difficult to move frequently,

it is likely that the workers moved from block to block rather than transporting the stones between workstations. Both of these major production streams would have needed to handle roughly 500 blocks per day.

In addition, temporary stockyards would have been indispensable to accommodate work-in-progress, variations in block size, and fluctuations in the labor required per block. These storage areas must have held hundreds or even thousands of blocks at any given time.

From quarrying to shaping, from shaping to transport, and from transport to the pyramid itself, the entire sequence—including intermediate stockyards—would have required a layout designed to minimize backtracking and detours, ideally forming a single, straight, uninterrupted logistical corridor.

Next, the transport route itself had to be prepared. Moving 500 large blocks per day is comparable to a modern road carrying 500 heavy trucks daily. Such a route would have required durable surfacing and would have been a core infrastructure element supporting mass production. Mudbrick, used extensively for paving and scaffolding, would also have required transport routes from the Nile floodplain to the worksite.

To maintain throughput and reduce heavy manual labor, the Egyptians must have developed equipment to improve efficiency—mechanisms for breaking rock with strong impact, devices for flipping blocks during shaping, and various tools and fixtures. These devices would not have been isolated; many identical units would have been deployed to create overall production capacity.

The following sections examine these methods and tools in detail, reconstructing the production system by imagining the processes and equipment that would have been necessary.

2. Quarrying of Stone Blocks

The stone used in the greatest quantities for pyramid construction was the limestone core blocks. From Dahshur to Giza, the total number of

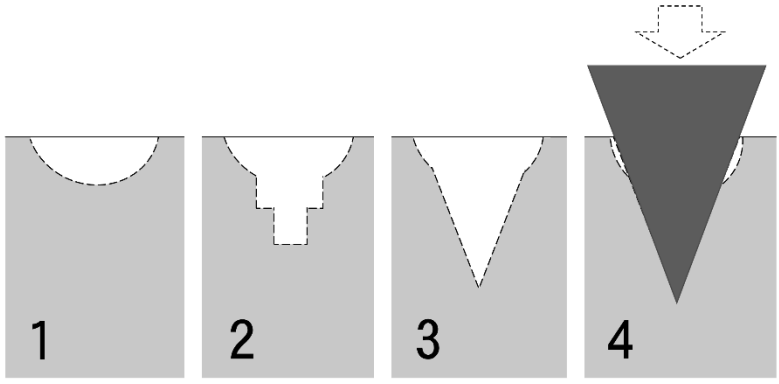


Fig. 2-2. Conceptual diagram of the stone-splitting process.

limestone blocks used in the large pyramids may have approached ten million.

The limestone quarried at Giza is classified as calcitic limestone. Calcite is well known for forming transparent rhombohedral crystals, and both limestone and calcite consist of calcium carbonate. As sedimentary rocks, they contain natural bedding planes formed during deposition.

In actual quarrying, these bedding planes were frequently exploited to split the stone. In this respect, limestone differs fundamentally from granite, an igneous rock with a dense structure and no bedding planes.

Because the unfinished obelisk at Aswan is such a famous example, detailed explanations of granite-quarrying techniques are abundant. However, the methods used for limestone were quite different. For this reason, the present book focuses specifically on the techniques used to quarry limestone.

The initial stage of stone splitting was likely as shown in Fig. 2-2. A block of diorite—harder than the limestone itself—was struck against the edge where the limestone block was to be cut, or the limestone was pounded with a stone hammer to crush the surface and create a depression (2-2-1).

This depression was then deepened using copper chisels, copper picks,

or stone hammers (2-2-2). This method is strongly supported by archaeological evidence: traces of partially worked limestone and large quantities of worn, rounded diorite hammerstones have been found around quarry sites.

At this point, however, I question the conventional view that the work shown in 2-2-2 was simply extended further—using chisels and picks to dig deeper and deeper until a long, narrow groove was formed.

To reconsider this, I imagined myself as a laborer working in the quarry.

The task of quarrying was to cut and extract large stone blocks—an ongoing struggle against the overwhelming weight of the material compared with human strength. In the early stage (2-2-1), when workers were striking the rock with hammerstones or pounding it with diorite blocks, it is natural to think that increasing the weight of the tool would increase its destructive power. But it would be physically impossible to use a hand-held tool weighing several tens of kilograms for any sustained period. The desire to use an even heavier object—something that could deliver greater force without relying solely on human strength—would have arisen almost inevitably.

What came to my mind was the yoitomake, a traditional Japanese gravity hammer still used today in places where heavy machinery cannot be brought in. As shown in Fig. 2-3, a frame is built from logs, and a heavy stone suspended by ropes is lifted by a group of workers and then

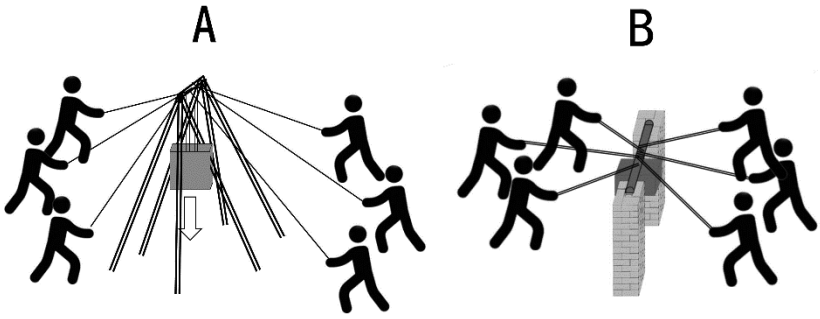


Fig. 2-3. Conceptual illustration of a yoitomake-type gravity hammer.

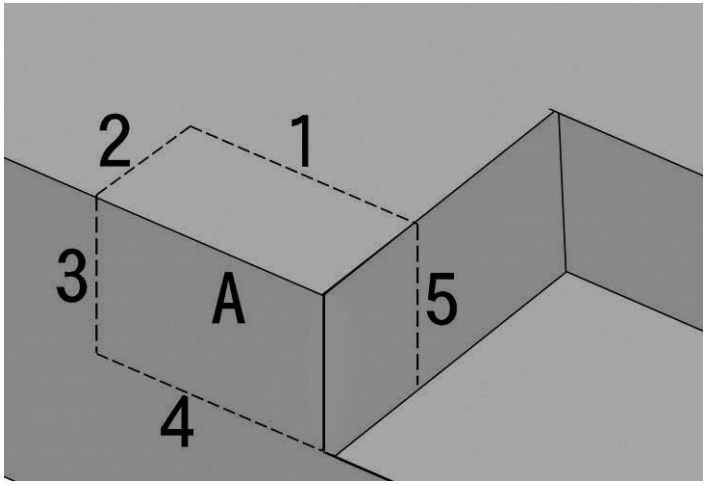


Fig. 2-4. Conceptual diagram of the preparatory stage of limestone quarrying.

dropped in unison with a shouted rhythm. This technique is used for tasks such as driving piles or leveling ground.

However, considering the material constraints of ancient Egypt, even constructing the wooden framework itself would not have been easy. For this reason, I believe that the more practical approach would have been to build square pillars made of stacked mudbricks, as illustrated in Fig. 2-3B. Mudbrick pillars could be constructed quickly, in large numbers, and with materials readily available at the site.

The next section describes how the actual fracture of the stone blocks may have been carried out.

The method of quarrying inferred from the remains found at ancient quarry sites is illustrated in Fig. 2-4. In this diagram, A represents the block of limestone to be extracted. The front side (lower left) and the right side should be understood as already quarried away.

In this situation, the preparatory work consisted of cutting grooves at positions 1, 2, 3, and 5. Position 4 corresponds to a bedding plane, but a shallow groove would also have been made there to ensure that the block would fracture reliably along the intended bedding plane.

As for the work of cutting these grooves, the use of copper chisels and

copper picks—relatively weak tools—was likely supplementary. The primary method would have been to crush the limestone by striking it with diorite hammerstones or pounding it with diorite blocks, which are harder than limestone. Rather than "cutting," the process was essentially breaking and pulverizing the rock. This interpretation is strongly supported by archaeological evidence: traces of partially worked limestone and large quantities of worn, rounded diorite hammerstones have been found around quarry sites.

In addition to the methods shown at positions 3, 4, and 5 in Fig. 2-4, it is possible that the side grooves of the limestone block were created using a technique like that illustrated in Fig. 2-5. In this method, a heavy stone is suspended and swung like a pendulum, gaining speed before striking the intended fracture surface.

The principle is similar to a playground swing: when the suspended stone reaches the vertical position, workers push it from behind, gradually increasing its amplitude. As the swing grows larger, the stone acquires significant gravitational acceleration. This allows even a stone too heavy to lift by hand to be accelerated easily, producing a powerful impact. Another advantage is that the pendulum delivers repeated blows to the same point, ensuring consistent and stable impact on the groove.

The above describes the preparatory stage of creating grooves to guide

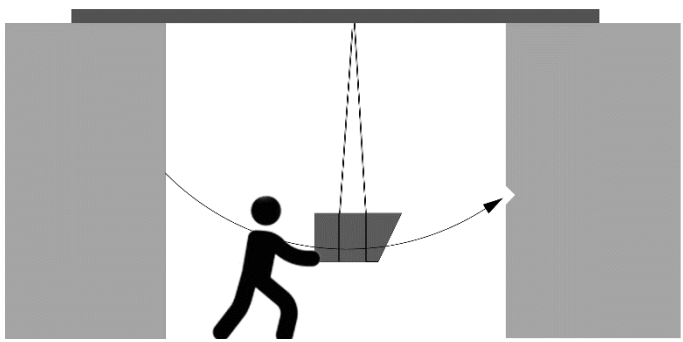


Fig. 2-5. Conceptual diagram of a pendulum device for crushing the side of a limestone block.

the fracture. However, to actually break the limestone along these grooves, an impact far greater than human strength alone could provide was required. The next section discusses the method used to achieve this fracture.

In the final stage of quarrying—separating the block from the bedrock—the most effective method is to apply a strong impact force. To illustrate this, let us assume that the limestone block to be extracted (corresponding to block A in Fig. 2-4) measures approximately 1.5 m in width, 1 m in depth, and 1 m in height. Because this is not a topic commonly discussed in general literature, I consulted a contractor who frequently performs stone-splitting work.

In Japan, there is a long tradition of placing large ornamental stones in gardens, and until about thirty years ago this was common even in private homes. I have purchased two pre-owned houses myself, both of which had large garden stones. When arranging for their removal, I asked the contractor about the actual methods used for splitting such stones.

Since heavy machinery cannot enter private residential lots, the standard procedure is to break the stone into smaller pieces before removal. The method involves drilling holes about 10 cm apart and roughly 5 cm deep along the intended fracture line, inserting iron wedges called seriya (approximately 10 cm long), and then hammering them in gradually and evenly. According to the contractor, even a stone of about 1 m^3 can be split effectively using this technique.

In ancient Egypt, of course, iron wedges were not available. However, the contractor noted that if one first created a substantial groove by striking the stone and then drove a wedge into it with sufficient impact force, the stone could indeed be fractured. When I described the yoitomake device to him, he immediately understood and remarked, “With something like that, you could split it easily.” In other words, modern practical knowledge confirms that with adequate impact energy, both limestone and granite can be broken—an insight highly relevant to understanding ancient techniques.

The contractor further stated that the grooves at positions 1, 2, 3, and 5 in Fig. 2-4 would need to be only about 10–20 cm deep, and that groove 4, if it coincided with a natural bedding plane in the limestone, could be as shallow as 10 cm. With grooves of this depth prepared, a strong blow delivered to a stone wedge inserted into groove 1 would be sufficient to detach the block. Since the total grooved area amounts to only 0.95 m^2 out of the 4 m^2 comprising the back (1.5 m^2), left side (1 m^2), and bottom (1.5 m^2), this may seem implausible at first glance.

However, this becomes understandable once we recognize that the grooves do not themselves cut the block free; rather, they serve merely as "initiators" that guide the fracture. Their function is to predetermine the fracture plane and concentrate stress along it. The actual separation occurs through the rapid propagation of cracks generated by the powerful impact applied to the wedge.

In modern Japan, the standard method for splitting stone by hand involves drilling holes and inserting iron wedges (seriya). Although ancient Egypt did not have iron wedges, it was certainly possible for them to drill holes into stone. A wall painting in the tomb of Rekhmire at Luxor, dating to the New Kingdom, depicts craftsmen using a bow drill to bore holes in wooden furniture. Moreover, traces of drilled holes have been

Fig. 2-6. Bow-drill scene from the Tomb of Rekhmire, Luxor (Metropolitan Museum of Art, Object Number 31.6.29, Rogers Fund, 1931, public domain).

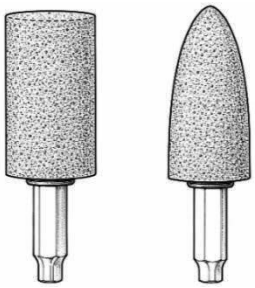


Fig. 2-7. Conceptual diagram of a mounted abrasive stone for drilling

found in the limestone blocks of Khufu's mortuary temple at Giza.

According to the contractor I consulted earlier—who frequently performs stone-splitting work—if the purpose is to create a fracture-initiating groove, drilling a series of holes at intervals of about 10 cm is actually more effective than cutting a continuous groove.

In ancient Egypt, when using a bow drill to make such holes, the stone would not have been cut directly by a metal bit. Instead, the drilling action would have been achieved by quartz sand packed at the tip of the wooden drill shaft. Because the wooden shaft is soft, the quartz grains embed themselves into the wood under pressure, effectively turning the tip into a primitive mounted abrasive stone. Although the idea of drilling limestone with a wooden rod seems counterintuitive, the presence of quartz sand makes the mechanism entirely plausible.

With these considerations in mind, I obtained a sample of limestone, No. 6 silica sand, and a 5-mm-diameter dowel made of soft willow, and carried out a drilling experiment using an electric drill.

The result, shown in Fig. 2-8, was, frankly, disappointing. After about three hours of work, the hole reached only 6.1 mm in depth (A). One thing I noticed during the experiment was that the wooden dowel wore down far less than expected, whereas the silica sand deteriorated quickly—presumably because its edges were rounded off as it rotated. I had hoped that the sand grains would embed themselves into the wood and act like a bonded abrasive stone, but that did not happen.

In the end, the process resembled polishing more than cutting. It is

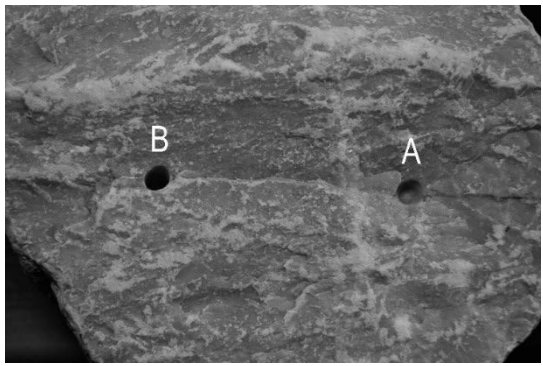


Fig. 2-8. Results of the experiment drilling a hole into limestone

possible to make a hole, but in terms of throughput, the method is hardly practical.

For comparison, I drilled the same stone using a steel drill bit: 12 mm in two minutes (B). With the metal bit, limestone powder immediately spurted out around the hole, making it clear that the material was being cut efficiently. The experiment reminded me just how soft limestone is as a rock—and how incomparable the wooden-rod-and-sand method is.

Things rarely work out exactly as they do in one's head, a fact I was reminded of once again.

If we assume a stone wedge approximately 30 cm long, inserted at position 1 in Fig. 2-4, and apply the yoitomake method shown in Fig. 2-3B—dropping a 100-kg stone from a height of 1 m above the wedge—the impact energy delivered to the wedge would be about 980 joules. If the wedge is driven in by 1 cm, the estimated instantaneous load would be roughly 10 tons.

Whether this is sufficient to achieve fracture in a single blow is uncertain, but each impact would propagate microcracks within the rock, gradually extending the fracture front. The yoitomake is inherently a device designed for repeated impacts, and through repeated hammering of the wedge, the rock would inevitably be forced into fracture by the physics of crack propagation.

However, whether the block fractures exactly along the intended

groove is not guaranteed. Limestone contains not only bedding planes but also vertical and oblique joints. If the impact energy acts more strongly along one of these joints than along the prepared groove, the block may fracture in an irregular shape. The yield rate would therefore not have been 100 percent. Moreover, the spacing of bedding planes is not uniform; even if one desired a block 1 m thick, there might not be a bedding plane at exactly that depth, and even if one existed, the fracture would not necessarily follow it as expected. Thus, it is more realistic to assume that the resulting blocks varied considerably in thickness.

An important consideration here is whether blocks that did not fracture as intended were treated as rejects. The answer to this would greatly affect the overall yield. I suspect that, rather than discarding such blocks, the pyramid construction site maintained stockyards where blocks of varying thickness were sorted and stored. (See Column 1 on page 33.)

A commonly repeated explanation in popular books on ancient Egypt is that wooden wedges were driven into grooves and then soaked with water, causing them to swell and split the limestone.

I am skeptical that this method was truly practical. While dry wood does expand when wetted, woods with high swelling ratios tend to be soft and easily crushed under hammering. Such wedges would deform before generating enough pressure to fracture limestone. Conversely, dense hardwoods have low swelling ratios and therefore cannot generate significant stress. Levering with wood or copper tools also seems implausible, given the limited strength of such materials. More importantly, static stresses from swelling or levering are far weaker for rock fracture than the instantaneous stresses produced by impact. From the standpoint of stone-production throughput, the swelling-wedge hypothesis appears unrealistic. Even if the method succeeded once, that does not imply it could be applied 2.3 million times.

3. Cutting and Polishing of Stone Blocks

The fact that limestone blocks were extracted not by cutting but by

fracture means that they could not be used in pyramid construction without further processing. Moreover, the required degree of precision differed greatly between core blocks and casing stones.

When comparing the pyramids of Dahshur and Giza individually, the core blocks show considerable variation, and the similarities are fewer than one might expect. Nevertheless, because the structures were built by stacking stones, several common requirements emerge. The upper and lower faces of each block needed to be flat and parallel to within a few centimeters, and the blocks within each course were made to a uniform height, even though the height of each course itself did not need to be constant.

The side faces often remain irregular, in some cases close to their fractured state. However, in the Pyramid of Khufu, it is clear that even the core blocks received a degree of rough dressing.

Casing stones, by contrast, formed a tightly interlocking shell that provided structural integrity. Their required precision reached the millimeter scale, and the outer surfaces—exposed to sunlight—were likely polished to a near-mirror finish to create a reflective sheen.

Since the extraction process produced fractured surfaces rather than cut ones, the resulting faces—except along bedding planes—would inevitably have had irregularities on the order of 10 cm. Even bedding planes would not always separate cleanly.

Thus, before true cutting could begin, the first step must have been to knock off protrusions and roughly shape the block. This was probably done by pounding with dolerite hammerstones, a method widely accepted in conventional Egyptology.

In the cutting stage, traditional explanations emphasize hand tools such as copper chisels and quartz sand. I have long questioned this view. Relying solely on impact risks producing unintended large cavities due to microcracks or heterogeneous rock composition. Eventually, one must transition to filing, chiseling, and abrasive finishing using quartz sand.

In Japan, whetstones are ubiquitous, and the association between

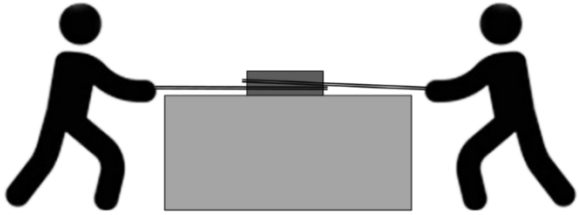


Fig. 2-9. Conceptual diagram of finishing stone with stone

sharpening and the use of abrasive stones is immediate. Coarse to fine whetstones are readily available. This led me to consider whether the Egyptians might have finished stone surfaces by rubbing stone against stone.

When sharpening a blade on a whetstone, one presses the blade firmly against the stone, especially during coarse grinding. If one were to finish stone using stone, it would be more efficient to rely on the weight of the stone itself rather than human force during the coarse-grinding stage.

Fig. 2-9 illustrates a hypothetical method in which a roughly dressed block of granite—or another hard stone—is used together with quartz sand to finish the surface of a limestone block. Two workers pull a rope alternately, causing the granite block to slide back and forth across the limestone surface. Since limestone has a Mohs hardness of about 3, while granite and dolerite range from 6 to 7, and quartz sand used as an abrasive is also around 7, the limestone surface is gradually worn down, whereas the granite tool experiences relatively little degradation. In other words, the granite block possesses sufficient durability to function effectively as a polishing tool.

The principal advantage of this method is that it allows large, flat surfaces to be finished efficiently.

Fig. 2-10 presents a hypothetical large-scale application of the same principle. Stones A, B, and C represent the blocks to be finished. D is a slope constructed of sun-dried mudbricks. After stone A is hauled to the top of the slope, it is slid across stones B and C, thereby shaving down the protrusions on its underside. If the inclines of stones B and C are kept

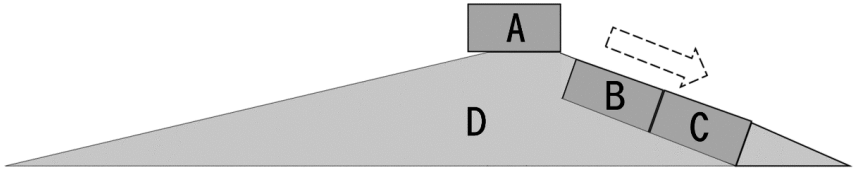


Fig. 2-10. Conceptual diagram of a method for finishing quarried stones using a slope

gentle, stone A will not slide uncontrollably; instead, workers can pull it with ropes and control its movement.

Although this method requires a sizable setup, I believe that such production equipment would have been entirely reasonable in a process that needed to mass-produce stone blocks on the order of one million units.

At the end of this chapter, I would like to comment on the jigs and tools proposed here. These are ideas I developed based on what would have been "useful to have," and I cannot claim that they actually existed in ancient Egypt. However, in modern mass-production environments, such jigs and tools often arise naturally from the ingenuity of workers on site—a manifestation of the continuous-improvement mindset known as kaizen.

Fig. 2-11 illustrates a jig designed to level the outer face of a casing stone, thereby facilitating the polishing process. The slope angle of each

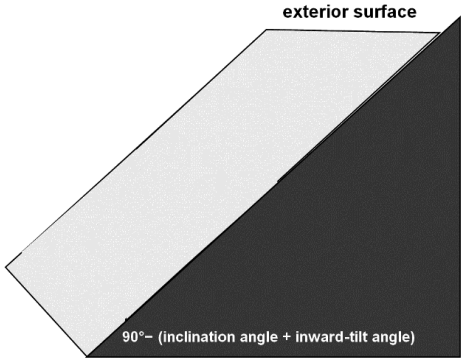


Fig. 2-11. Jig for finishing the casing surface

pyramid was essentially fixed for that particular monument, and when inward-leaning courses were employed, the inward tilt angle was likewise predetermined. Inward-leaning masonry creates a structural condition in which the weight of the stones pulls them toward the interior, producing a highly stable configuration—a technique commonly used in stone walls even today.

However, when casing stones must be produced in large quantities, it is far more practical to polish the surface in a horizontal orientation rather than working directly on the complex compound angle defined by the pyramid's slope and the inward tilt.

Fig. 2-12 illustrates a device designed to flip large stone blocks. Core blocks could weigh as much as six tons, and turning such masses over by human power alone—using levers or ropes—would have been extremely difficult. In the figure, the block is first hauled to the top of the slope and then allowed to slide toward the limestone block at point C, which serves as a pivot. When the sliding block strikes point D, its momentum is converted into a rotational moment, causing it to flip over and fall toward point E. In this way, gravity is used to reverse the upper and lower faces of the block.

Given that quarrying and dressing were carried out daily on a massive scale, it is likely that even more innovative, unique, or large-scale mechanisms and techniques were devised at the work sites.

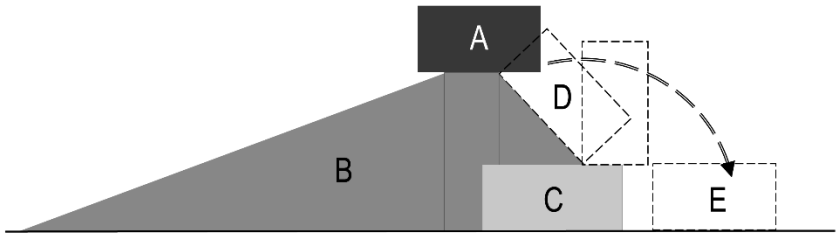


Fig. 2-12. Equipment for flipping stone blocks

Column 1. The Thickness of Pyramid Core Blocks Was Not Uniform

Visitors to Khufu's Pyramid at Giza will know that the thickness of the core blocks is far from uniform. The lowest courses consist of very thick blocks, and although the blocks generally become thinner toward the top, the change is not a simple monotonic decrease.

Petrie measured the thickness of each course in detail, and his drawings—reproduced in Fig. c-1—clearly show that the block thicknesses are irregular. Notably, the blocks in the 19th course and those above the 35th course are significantly thicker. This may reflect intentional adjustments made to accommodate the internal structural design. Even in the higher courses, however, the thickness varies considerably, and the pattern is neither continuous nor regular. Nevertheless, the horizontal planes of each course are maintained with great precision.

Limestone fractures horizontally along bedding planes, as expected for a sedimentary rock, but in practice the stone does not always break cleanly along the intended plane. Some blocks would have ended up thicker or thinner than desired.

I suspect that at the actual quarrying sites, large quantities of such "off-spec" blocks were stockpiled, and that the heights of the courses were determined based on the available stock. For example, although the core blocks near the base of the pyramid are extremely thick, blocks that fractured thinner than expected may have been stored and later used in the upper courses.

Significant time must have been spent preparing the construction site—grading the approach roads, leveling the bedrock foundation, stockpiling sun-dried mudbricks for ramps, dredging Khufu's harbor, and building jetties. Quarrying and stockpiling of core blocks likely began very early, and by the time large-scale stone setting commenced, a substantial inventory of blocks would already have been accumulated.

To maintain construction throughput, it was essential to avoid halting

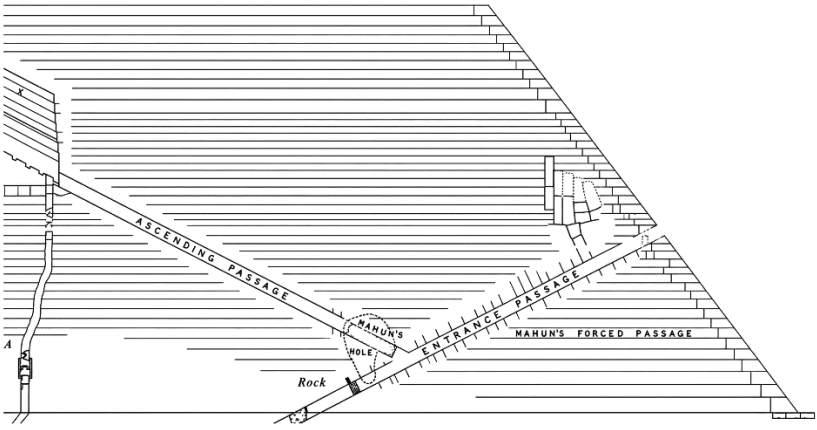


Fig. C1-1. Heights of the stone courses of the Pyramid of Khufu (traced from Petrie, The Pyramids and Temples of Gizeh, 1883)

downstream processes due to material shortages. For this reason, it is unlikely that quarried and dressed stones were sent directly to the building site without intermediate storage. A large stockyard must have existed.

It would be as unreasonable as a restaurant running to the butcher only after a customer orders lamb. A restaurant can apologize and offer an alternative dish, but pyramid construction could not proceed if the supply of stone ran out.

The pyramid project combined a massive stone-production operation with a large-scale civil-engineering site. It is therefore reasonable to assume that, just as in modern manufacturing—where factory inventory and distribution inventory buffer production and assembly—an intermediate stockyard existed between the quarrying/dressing operations and the stone-setting operations.

CHAPTER 3

Considerations on Overland Transport of Construction Materials

1. Paved Roads

The heaviest overland transport during pyramid construction occurred between the quarries and the pyramid sites. However, substantial traffic must also have existed along shorter routes—for example, transporting materials and food from Khufu's harbor and the Nile riverbank to the construction site, or moving sun-dried mudbricks manufactured along the river.

Popular books on ancient Egypt often describe such transport simply as being carried by people or dragged on wooden sledges. Yet ever since walking across the sandy ground at Giza and Dahshur, I have doubted this explanation.

Hollywood films often depict desert scenes shot in the dune fields of Morocco, leading many to imagine desert sand as fine, loose grains into which one's feet sink deeply. But the sand around Giza and Dahshur is quite different. Although there are occasional pockets of soft sand in hollows or at the foot of hills, these are exceptions.

Most of the ground consists of sand mixed with limestone fragments, as shown in Fig. 3-1, and one's feet hardly sink at all.

This raised a question for me: Could a wooden sledge really be dragged over such terrain?

On loose sand, wetting the surface to reduce friction is understandable. But on sand mixed with sharp limestone fragments, a wooden sledge would quickly splinter and deteriorate, making transport far from easy.

Fig. 3-1. Sandy ground at Dahshur (photographed in 2008)

The famous relief in the tomb of Tehutihetep shows a large statue being hauled on a sledge by many workers, but that scene represents a ceremonial event, not a daily operation. For a one-time ritual, it would be more practical to sieve sand or bring uniform sand from a Nile sandbar than to pave a road. However, for routes with heavy, continuous traffic, it is natural to assume that paving was carried out—and indeed, remains of paved pathways have been found.

I believe that the construction roads were not paved with stone slabs but with sun-dried mudbricks, which were available in large quantities and suitable for simple paving.

Furthermore, I propose that stone blocks were transported not on sledges but on rollers over these paved roads. The following is a proposed specification for such roads, assuming the need to sustain a massive throughput—233 blocks per day—even under the most conservative calculations.

Fig. 3-2 illustrates the imagined process of constructing a paved road using sun-dried mudbricks.

A: Ground leveling.

The essential requirement is to maintain horizontal alignment and avoid unevenness—similar to railway subgrade preparation.

Dahshur's terrain is mostly flat sandy ground, requiring little cutting or filling, making leveling extremely easy.

Giza, by contrast, has many limestone outcrops, so some excavation would have been necessary.

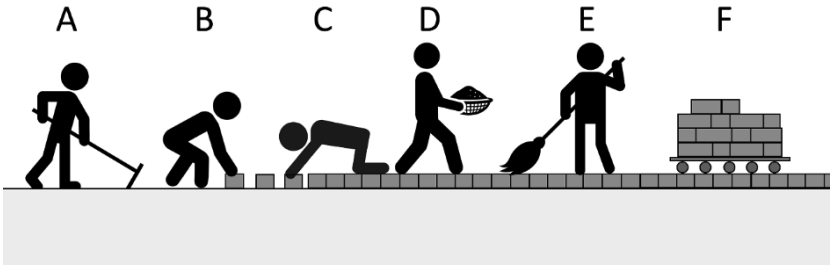


Fig. 3-2. Conceptual diagram of road construction using sun-dried mudbricks

Even if the route became somewhat indirect, keeping the gradient below 5/100 (2.86°) would greatly ease transport. This slope is noticeable when walking but manageable even for elderly people, and on a bicycle it can be climbed without standing on the pedals.

B: Transporting and staging the mudbricks.

Assuming bricks of 30 × 15 × 10 cm weighing about 8 kg each, even a 10-meter carrying distance would be heavy labor. This may have been the most manpower-intensive task.

C: Laying the bricks.

Workers pull the staged bricks into place and fit them tightly. Avoiding unevenness is essential, though gaps of a few millimeters would be acceptable.

D: Transporting sand for infill.

Since the entire area is sandy, the transport distance is minimal.

E: Filling gaps with sand.

F: Completed mudbrick pavement, over which materials—including mudbricks themselves—are transported using rollers.

For ordinary stone-transport roads, a width of 2 meters would suffice even for large core blocks. However, considering waiting areas and passing during transport, I assume a width of 3.6 meters, created by laying 12 bricks (30 cm wide) side by side.

A team of six workers, each responsible for two bricks, could complete one row in about four minutes. This advances the pavement by 15 cm. Thus:

40 minutes → 1.5 m

11-hour workday → 24.75 m

30-day month → 742.5 m

A group of about 20 workers could likely perform this operation. Brick consumption would be:

1 day → 1,980 bricks

1 month → 59,400 bricks

As noted in Chapter 1, 1,000 workers could produce 100,000 mudbricks per day, so 59,400 bricks per month is trivial. Mudbrick production would not have been a bottleneck.

Even the relatively distant Menkaure quarry is only 1.5 km from the pyramid. With five such road-building teams working in parallel, the major road network of Giza could have been paved within a few months.

The first paved road was likely the route from the Nile riverbank—where mudbricks were produced—to the Giza construction site.

Because the sandy ground at Giza and Dahshur is firm and mixed with limestone fragments, it does not easily deform under load. Once paved with mudbricks, the surface would not sink readily. Mudbricks are extremely strong under vertical compression, making such roads more durable than they appear.

Although mudbricks are weak against torsion and may crack, even broken bricks remain as compacted fill and do not significantly reduce road strength. Moreover, because the structure is simple—bricks laid on sand and gaps filled with sand—damaged sections could be repaired quickly by removing bricks, leveling the sand, and replacing them.

Thus, the durability of mudbrick roads likely depended more on ease of maintenance than on inherent structural strength.

At Giza, remains of what appear to be mudbrick-paved roads still exist. In front of Menkaure's pyramid, a mudbrick causeway—traditionally attributed to his successor Shepseskaf—has been identified. However, Dr. Mark Lehner has suggested that because this mudbrick road terminates at an older quarry from Khufu's time, it may actually have been a stone-transport ramp.

Fig. 3-3. Conceptual diagram showing many workers pulling a stone block

2. Wooden Rollers

Numerous experiments have been conducted in the past in which many people drag Egyptian stone blocks. The NOVA pyramid-building experiment also attempted this. Yet every time I read the reports or watch the videos of these experiments, I feel not merely doubt but a strong sense of discomfort.

The reason is that these experiments generally resemble what is shown in Fig. 3-3. The people in Fig. 3-3 are not actually pulling the stone with arm strength; they are using a falling-forward motion that relies on body weight. With enough people, the stone will indeed move. It does serve as "evidence that it moved."

However, the question immediately arises: Do they really believe this work could be continued for 11 hours a day, every day, for seven months? There is a vast gap between "being able to move it once" and "being able to move it continuously for long hours every day." What they demonstrated is essentially a one-time, unsustainable show.

From a mechanical standpoint, this motion involves repeatedly pulling with body weight, stopping, pulling again, stopping—an endless battle against static friction. Static friction is always greater than kinetic friction, and this method demands the maximum static friction every time. Rationally, one should maintain motion and stay within the lower kinetic-friction regime.

Furthermore, to achieve the throughput required to transport several hundred core blocks per day, an enormous workforce would have been necessary. For a few dozen stones, increasing manpower might work. But for several hundred, tens of thousands of workers would be required

solely for stone transport. Forcing such heavy labor every day during the inundation season—summer—would be utterly unsustainable. This is likely why, until a few decades ago, pyramid construction was believed to rely on slave labor. A mistaken assumption about construction methods produced a mistaken view of history.

Let us now discuss friction coefficients.

Assuming a weight of 3 tons:

The static friction coefficient for a stone placed on sand is about 0.6–0.8, requiring 1800–2400 kgf to start moving it.

A wooden sledge sliding on wet sand has a kinetic friction coefficient of about 0.2–0.3, requiring 600–900 kgf.
(kgf is a conventional unit representing the force equivalent to the weight of a mass in kilograms.)

However, in rolling motion, resistance decreases dramatically. Because bearings and axle technology had not yet developed in the Old Kingdom, and because axle strength was insufficient, transporting multi-ton stones on wheeled carts was impossible. Without wheels, the only rolling-based transport method available was the roller. But rollers are useless on sand: they sink and fail to rotate. Thus, rollers require a paved transport road.

Roads paved with mudbricks do exist archaeologically, but after 4000 years mudbrick often erodes back into soil, so such remains are not universally preserved. For this reason, Egyptology has rarely considered

Fig. 3-4. Wooden roller exhibited at the Metropolitan Museum of Art (Courtesy of The Metropolitan Museum of Art, New York. Accession Number: 26.3.308.)

rollers, and the famous relief of hauling a colossal statue on a wooden sledge from the tomb of Tehutihetep has overshadowed alternative transport methods.

Yet the Metropolitan Museum of Art displays a roller discovered beneath a limestone sarcophagus in a Middle Kingdom tomb at Thebes. The MET cautiously states that it was "likely used to aid in its transport," but the object itself is labeled as a roller. Given its position beneath the sarcophagus, the likelihood is high. The MET lists its length as 65 cm; from photographs, the diameter is about 7 cm.

Among the MET's vast holdings—many not on permanent display—the fact that this extremely modest wooden roller continues to be exhibited carries a certain significance. It suggests that the MET is quietly highlighting the overlooked reality that rollers were used in ancient Egypt.

The rolling resistance of wooden rollers on a prepared surface varies with surface irregularities and the material of the rollers, but it can generally be expected to fall within the range of 0.05 to 0.1. Moving a 3-ton block therefore requires approximately 150 to 300 kgf of force.

To achieve a throughput of one block every 1.3 minutes, workers must be able to apply this force continuously and reliably. The challenge is not momentary exertion but sustaining a workable level of force over long periods. To investigate what might be feasible, I conducted a series of experiments at home using an exercise expander fixed to a pillar.

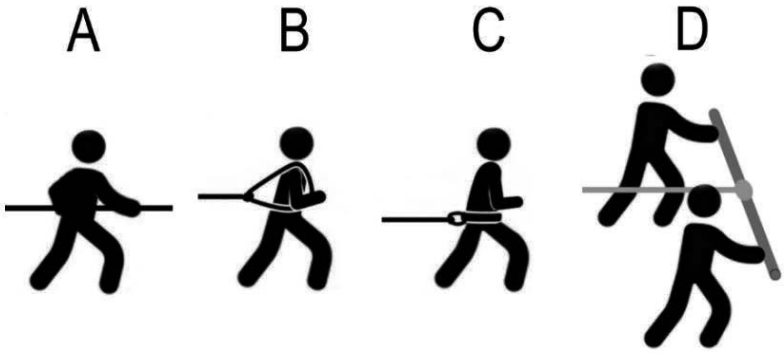


Fig. 3-5. Experimental methods for pulling loads

The first method, shown in Fig. 3-5 (A), involved pulling a rope held beside the body. Because the rope is positioned laterally, the wrist twists, and the method depends heavily on grip strength. Fatigue set in quickly. It is workable for short bursts but unsuitable for sustained labor.

Method B used shoulder straps, similar to wearing a backpack. This reduced the effort compared with A, but the load concentrated on the shoulders and clavicles, making it impractical for heavy or prolonged work.

Method C attached the rope to a wide hip belt, similar to the pulkka used in northern Europe. By transferring the load to the pelvis, this method significantly reduced bodily strain and proved far more comfortable.

However, while B and C are effective for an individual hauler, they present operational difficulties in coordinated group work—particularly the need to branch the rope radially.

The breakthrough came the next day, while I happened to be pushing a shopping cart. This led to method D: instead of pulling a rope, workers push a horizontal bar attached to the rope. This posture uses the palms rather than the grip, allows a forward-leaning stance, and enables workers to apply body weight. For short periods, one can even lean onto the bar, producing substantial force. The method is inherently suited to cooperative work and can scale to teams of twenty.

In posture D, a worker can push roughly 20 kgf for several tens of minutes, 15 kgf for sustained heavy labor, and about 10 kgf comfortably. With rolling resistance between 0.05 and 0.1, sixteen workers can therefore move a 3-ton block.

Transport routes at Giza—except for areas such as the western quarry—are generally 500 m to 1 km. Even at a slow speed of 2 km/h, the trip takes only 15–30 minutes, avoiding prolonged heavy exertion.

The principal drawback of method D is the large number of horizontal bars required. Because Egypt lacked abundant timber, suitable materials must come from sources not used for conventional carpentry.

The most promising candidate is the leaf stalk (rachis) of the date palm.

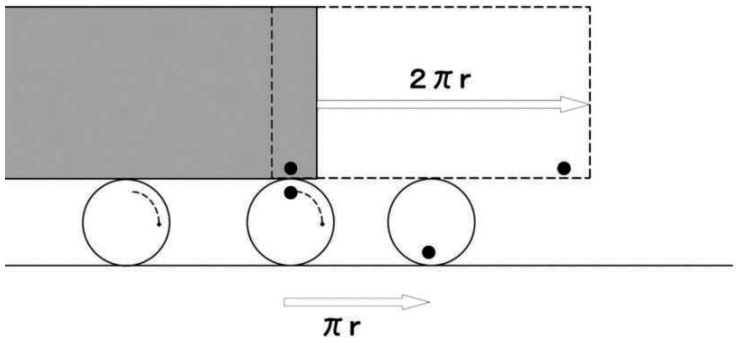


Fig. 3-6. Operation of rollers

These rachises can reach lengths of about 4 m, and historical examples show that they can be split and bundled to make benches or beds. At EXPO 2025 in Osaka, the UAE Pavilion imported more than two million date-palm rachises and bundled them into structural members roughly 1 m in diameter.

The spiky lower portion of a date palm trunk is the remnant of fallen leaf bases. As the palm grows, old leaves dry and fall away, providing an almost inexhaustible supply of dried rachises. A single rachis is not strong enough as a structural member, but bundling them with straw rope or papyrus yields adequate strength for use as horizontal bars. The bundled portion also provides natural cushioning for the hands.

Let us now consider how rollers function. Modern readers are familiar with wheels, but rollers behave somewhat differently. When a block moves over a cylindrical roller, friction causes the roller to rotate. A half-rotation advances the roller by πr, where r is the radius. The block also advances by πr relative to the roller, but because the roller itself moves forward by πr, the block advances a total of 2πr.

Because the block moves at twice the speed of the roller, the roller beneath the trailing edge is left behind. Rollers must therefore be supplied in front of the block, and those left behind must be carried forward.

Fig. 3-7 illustrates this situation. Worker A carries a roller from position B to the front, while worker C places rollers ahead of the block.

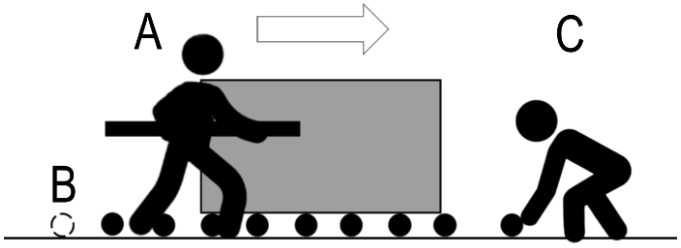


Fig. 3-7. Commonly imagined method of placing rollers

At first glance this seems workable, but as noted earlier, with method D the block can advance at about 2 km/h, or 0.56 m/s. If rollers are spaced at 30 cm, the block leaves behind nearly two rollers per second (1.85).

This makes tasks A and C extremely demanding. Task A can be mitigated by increasing personnel, but task C—placing rollers in front—cannot easily be shared among multiple workers and is difficult to sustain. Thus, the commonly imagined method shown in Fig. 3-7 cannot maintain a speed of 2 km/h.

I therefore considered a different approach: arranging rollers in advance and returning displaced rollers to their original positions. This concept is shown in Fig. 3-8.

In Fig. 3-8, when a block of length L moves to the right, each roller under it also shifts by L. For convenience, six rollers (A1–F1) are shown under a block of length L. Roller A1 moves to A2, F1 to F2, and so on. After the block passes, rollers remain behind. A roller at P2 only needs to be rolled back to P1. Since most pyramid blocks are under 2 m long, this return distance is small, and rolling the roller back is easy.

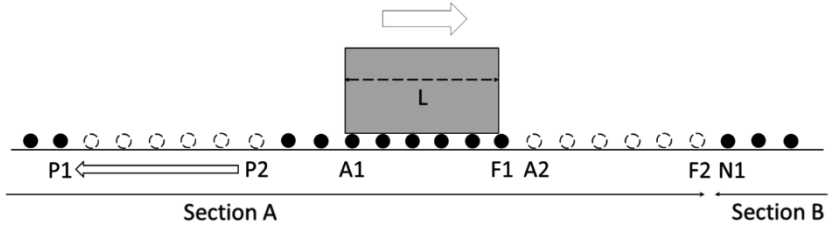


Fig. 3-8. Section-responsibility system and roller-position management

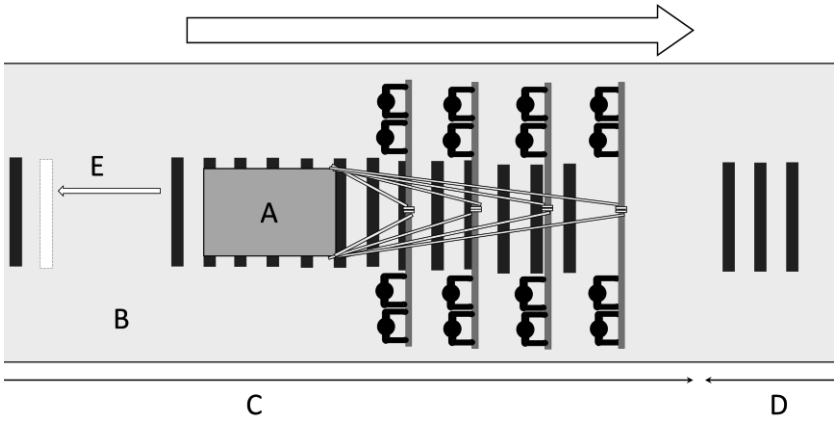


Fig. 3-9. Summary of transport concepts

Section B to the right of N1 is handled by another crew, and rollers there are already in place. Because block lengths vary, spacing must be adjusted at section boundaries by narrowing intervals or temporarily removing rollers.

With this method, restoring roller positions becomes easy, allowing uninterrupted transport.

However, this requires assigning workers to fixed sections. If 500 blocks per day are transported—one every 1.3 minutes—at 2 km/h, the spacing between blocks is 43.3 m. If two blocks occupy the same section, the system fails, so sections of about 30 m are practical. With two lanes, spacing doubles to 86.6 m, allowing longer sections and easier roller restoration.

Fig. 3-9 summarizes the ideas discussed so far. Block A is tied to a rope and pushed via a horizontal bar. Workers can step over rollers if spacing is around 40 cm, and with practice this becomes easy. For clarity, the figure shows workers arranged in four rows of four, though two rows of eight would also work.

In Fig. 3-9, A is the block, B is the mud-brick ramp, the towing method uses a horizontal bar, E represents workers restoring rollers, and C and D represent section boundaries. With a speed of 2 km/h and a frequency of one block every 1.3 minutes, spacing is 43.3 m, so sections are assumed

to be 30 m. Four workers per section suffice.

For a 600-m route, divided into 20 sections, 80 roller workers are needed. About 14 blocks occupy the route simultaneously, requiring 224 haulers. Thus, roughly 300 workers can transport blocks at 1.3-minute intervals, completing the 600-m route in 18 minutes. Allowing for return, rotation, and rest, a workforce of about 500 would be adequate to move 500 blocks per day on a single route.

In other words, each worker transports a 3-ton block over 600 m per day.

Finally, regarding the rollers themselves: they must be treated as consumables, subject to wear, deformation, and cracking. Imported cedar is out of the question, and even acacia, sycamore fig, and tamarisk are too valuable. The practical option is the core wood of the date palm.

Published data (Engineering Properties of Date Palm Trunk Applicable in Designing a Climber Machine) give compressive strengths of 4.5 MPa longitudinally and 1.1 MPa radially. Since rollers are made by slicing the trunk and shaping 10-cm-diameter cylinders, the relevant value is the radial strength of 1.1 MPa.

Supporting a 3-ton block on six rollers yields 500 kgf per roller. Assuming a 1-cm-wide contact strip over a 1-m block width gives 100 cm^2 of area, or 5 kgf/cm^2 (~0.5 MPa). This is below the proportional limit of 1.1 MPa, meaning deformation remains largely elastic and recovers as the roller rotates.

In this stress range, rolling resistance does not exceed 0.1 and likely falls within the assumed 0.05–0.1 range.

As for the towing rope: even with rolling resistance of 0.1, moving a 3-ton block requires 300 kgf. With four rows of four workers, each rope bears 75 kgf. In Chapter 1, I noted that a 20-mm rope with a safety factor of 1/15 has a strength of 80 daN, which is sufficient.

These considerations demonstrate that rollers made from the core wood of the date palm can indeed support the transport model shown in Fig. 3-9.

Column 2. "Excuse me, but how do you pronounce your name?"

In Japan, this is a question that occasionally comes up when exchanging business cards for the first time. It may be hard to believe for people from Western countries, but when a rather uncommon name is written in kanji, even Japanese people often have no idea how to read it. Place names in Kyoto are even more extreme—an entire parade of difficult and irregular readings. Uzumasa (太秦), for example, is something that even many Japanese cannot read.

What may be even more incomprehensible to Westerners is that Japanese people can still recognize written text even when they cannot pronounce it. They know the kanji themselves, so even if they do not know the correct reading, they will internally assign some arbitrary pronunciation—remembering 太秦 as something like "Futohata," for instance.

In Western countries, too, one might occasionally hear the question "Excuse me, how do you pronounce your name?" when encountering German, Polish, or French names such as Schwarzenegger. Superficially the phenomenon looks similar, but the underlying cognitive process is quite different. The intention behind the Western question is closer to "I cannot remember it unless I can pronounce it." Japanese people, on the other hand, will simply remember the written form even if they cannot pronounce it.

In Egyptological publications written in Western languages, it is standard practice to provide phonetic values alongside hieroglyphs. In this book, however, I have deliberately chosen not to include phonetic values. The reason is simple: even if phonetic values are provided, the transcription system is one that only trained Egyptologists can actually pronounce. For general readers, it offers little benefit. Moreover, even if an Egyptologist can pronounce it, there is no guarantee that the reconstructed pronunciation matches ancient Egyptian speech.

Hieroglyphs, however, can at least be recognized visually by Western

readers as symbols. For example, the birth name of King Khufu is written as , with the phonetic value Hwfw. Yet the transcription Hwfw does not even contain the letter K, nor does it include vowels. Ordinary readers cannot possibly read it aloud.

As for what represents—whether a sieve, a placenta, or something else—there are various theories. But is it not far easier simply to remember it as "something like a sieve, a chick, a slug-like creature, and a chick," and associate that cluster with Khufu?

For this reason, in the pages where the hieroglyphs appear, I have not added phonetic values. You do not need the readings; remembering the meaning is enough. For example:

represents sailing up the river with a sail

represents going down the river using oars

represents a boat

If you remember them by meaning, they fully serve their function as logograms.

CHAPTER 4

Water Transport on the Nile

In ancient Egypt, the movement of goods relied primarily on river transport along the Nile. This was a natural consequence of agricultural development, settlement, and urban growth along its banks.

The Nile flows from south to north, from Ethiopia and Sudan to the Mediterranean. Transport from Upper Egypt downstream required little more than surrendering to the current. Upstream navigation, by contrast, depended on sail power. Egypt is characterized by a persistent northerly wind blowing from the Mediterranean along the Nile Valley. These winds are especially stable during the summer inundation season, enabling boats to drift downstream with the current and return upstream under sail.

In winter, however, the northerlies are less reliable, and calm days occur. Between March and May, sudden westerly winds from the Sahara can bring dust storms, reduced visibility, and rapid temperature increases.

For this reason, any discussion of Nile transport—particularly the movement of heavy materials such as stone—must distinguish between downstream transport and upstream sailing.

Tura, the principal source of high-quality limestone, lies on the east bank of the Nile, whereas Giza and Dahshur lie on the west. Crossing the river was therefore unavoidable. Giza lies downstream of Tura, while Dahshur lies upstream. Transport to Giza could simply follow the current, whereas transport to Dahshur required either upstream sailing or an alternative route: crossing the river at Tura and hauling the stone overland southward. The latter was likely the preferred method.

Granite from Aswan presents a different case. The distance from Aswan to Giza, following the river's meanders, is roughly 1,000 km. Modern writers sometimes cite this distance as evidence of the difficulty of transport, but this reflects a modern misconception. Drifting downstream requires time, but little labor. The real operational burden lay in quarrying, hauling to the riverbank, loading, unloading, and final delivery. When time constraints are loose, spatial distance becomes a secondary concern—a point modern readers often overlook.

In modern maritime trade, the concept of FOB (Free on Board) separates responsibility: the shipper is responsible until loading, and the receiver thereafter. In ancient Egypt, communication between Aswan and Giza depended entirely on river traffic and was far from continuous. The quarrying crews would have worked steadily, while the receiving crews at Giza simply began work whenever a shipment arrived.

In such a system, the question "When will it arrive?" is meaningless. Ships were things that eventually drifted into view, and their arrival marked the beginning of work.

1. Memories of Flat-Bottomed Boats

Having lived in Yokohama for many years, I often saw a distinctive type of cargo barge known as the Daruma-sen moving slowly through the city's canals. With its extremely shallow draft and flat bottom, the vessel was designed for stability and ease of loading rather than speed. It was unsuitable for open seas and operated exclusively in sheltered bays and canals.

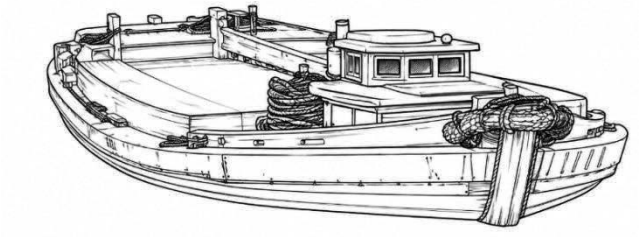


Fig. 4-1. Illustration of a Daruma-sen barge

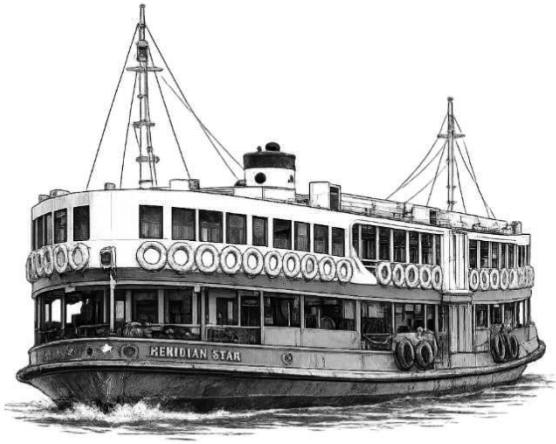


Fig. 4-2. Illustration of the Star Ferry

Another vessel that left a strong impression on me is Hong Kong's Star Ferry. Its unusually wide passenger deck, wooden benches, and two-level structure are distinctive, but its most remarkable feature is its double-ended design, which eliminates the need for turning the vessel around. This allows rapid docking and departure—ideal for high-frequency passenger transport across the sheltered waters between Hong Kong Island and Kowloon.

Both vessels share a shallow draft, which simplifies harbor construction and maintenance. The Nile, with its calm waters and gentle current of roughly one meter per second, would have favored similar designs. For cargo transport, stability mattered far more than speed.

The German Egyptologist Karl Richard Lepsius published a monumental twelve-volume survey of Egyptian monuments. Volume IV includes depictions of broad, shallow-draft cargo boats, likely from the Fifth Dynasty mastaba of Ptahhotep at Saqqara.

Although stylized, the depicted boat appears to be about six meters long and more than one meter wide. Archaeological evidence confirms that ancient Egyptians built flat-bottomed boats, including the famous solar boats. It is therefore reasonable to assume that even broader flat-bottomed vessels could have been constructed for short-distance cargo transport.

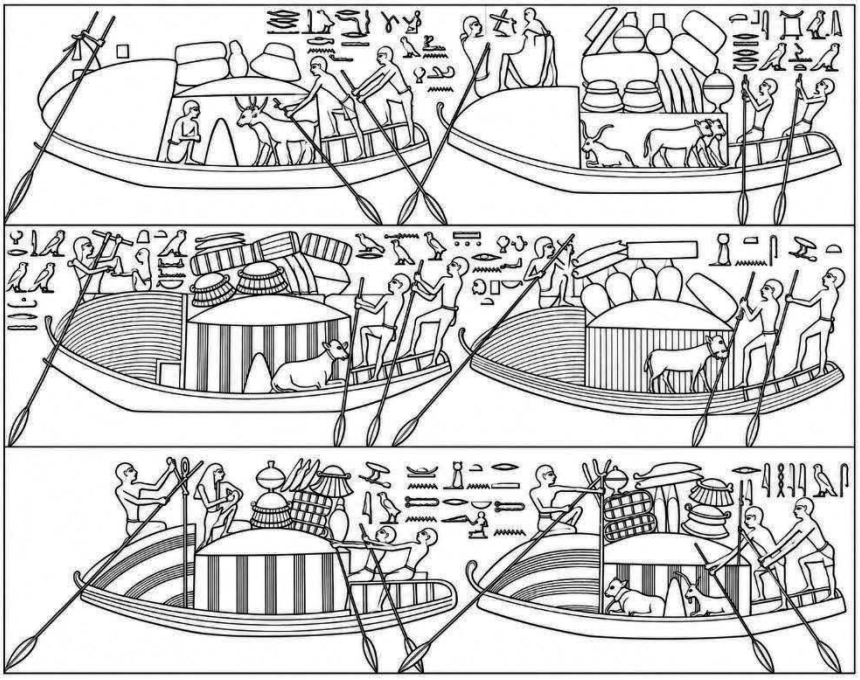


Fig. 4-3. Low-draft boat depicted in tomb art (Source: Traced from Karl Richard Lepsius, Denkmäler aus Aegypten und Aethiopien, 1849–1859, Abteilung II, Blatt 104b.)

A flat-bottomed boat six meters long and two meters wide could likely carry a block weighing around 2.5 tons. Since casing stones were generally smaller than core blocks, such vessels may have been the primary means of transporting Tura limestone to Giza.

2. Papyrus Rafts as an Alternative

Although no papyrus rafts for stone transport appear in Egyptian art, papyrus was abundant, and bundles of papyrus reeds could be lashed together to form a raft capable of carrying perhaps 1.5 tons.

My emphasis on small, shallow-draft vessels stems from the likely presence of extensive shallows along the Nile's banks, even during the

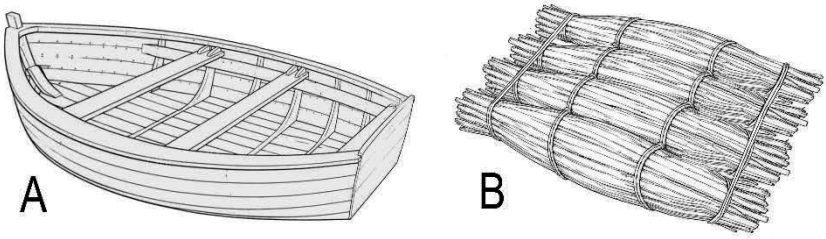


Fig. 4-4. Conceptual reconstruction of a flat-bottomed boat and papyrus raft

inundation. A flat-bottomed boat or raft could simply be run aground like a landing craft, providing a stable platform for loading and unloading stone.

Deep-draft vessels moored to a quay would have been far less practical. The shifting weight of stone during loading would cause dangerous rolling.

For the short 10-km journey from Tura to Giza—downstream and with favorable current—small vessels or rafts would have been entirely adequate.

Granite from Aswan is a different matter. Over a distance of 1,000 km, small craft would be impractical, and larger vessels must have been used. Massive blocks such as the ceiling stones of the King's Chamber or the great gabled lintels above the entrance would have required such ships.

But these exceptional stones represent only a tiny fraction of the total volume. The overwhelming majority of transported stone consisted of Tura limestone casing blocks.

3. Ancient Giza's Flood-Season Topography

A recent study, The Pyramid Builders' Waterways: Reconstructing the Ancient Topography of Khufu's Pharaonic Harbour at Giza, Egypt by Gamal Younes and colleagues at Aix-Marseille University, provides a highly informative reconstruction of Giza's flood-season landscape.

The square structure in the center is the so-called Khufu Harbor.

More intriguing, however, is the large basin immediately to its north.

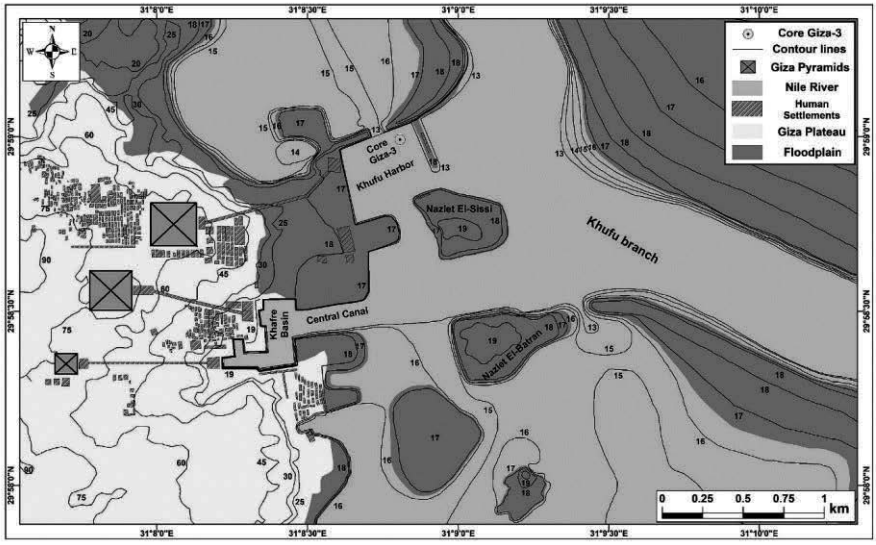


Fig. 4-5. Reconstructed paleogeography of Giza during the flood season in the Fourth Dynasty (Younes et al., Journal of Archaeological Science: Reports, 2024. Reproduced with permission from Elsevier Ltd.)

According to the reconstruction, this basin was connected to the Nile by a channel cut down to an elevation of 13 meters, with surrounding ground rising to about 15 meters. During the dry season, the basin would have emptied and become a depression. At peak inundation, the Nile could reach 17 meters above sea level, flooding the basin.

The southwestern edge of this basin lay only about 500 meters from Khufu's Pyramid.

I therefore propose that Tura limestone blocks, carried on shallow-draft boats or rafts, did not dock at the Khufu Harbor quay but instead were run aground along the southwestern shore of this basin, where unloading would have been far easier.

Even if the basin dried out during the low-water season, this posed no problem. Pyramid construction relied primarily on agricultural laborers during the inundation, when fields were underwater. An infrastructure usable only during the flood season would have been entirely adequate.

Fig. 4-6. Kuruwa, a small fishing port in Yokosuka, Japan (modified from Geospatial Information Authority of Japan maps)

In this sense, Khufu Harbor was not a single facility but a dual-structure port, consisting of:

a quay for deeper-draft vessels, and

a broad, shallow basin for small boats and rafts.

This arrangement is common in small Japanese fishing ports, such as the one shown in Fig. 4-6, where a deep-water pier coexists with a shallow beaching area for small craft. Having grown up seeing such harbors, I immediately recognized the pattern when examining the Giza reconstruction.

These considerations suggest that Khufu's harbor was not a facility that operated year-round. Rather, it must be understood as a seasonally functional port, whose usability fluctuated dramatically with the Nile's annual cycle of inundation and low water.

During the lowest stages of the river, the harbor basin would have partially or completely dried out, becoming a mudflat. Under such conditions, navigation was impossible, and any dredging or excavation required for harbor maintenance would likely have been carried out precisely during this period, when the water had receded.

Conversely, at the peak of the inundation, the Nile could rise to approximately 17 meters above sea level, as indicated in the reconstruction by Younes and colleagues. Portions of the harbor's shoreline may have been temporarily submerged, again limiting its functionality.

In short, Khufu's harbor should be regarded not as a permanent, continuously operating installation but as a hydrologically constrained infrastructure, usable only during the moderate phases between extreme high and low water. This interpretation aligns well with the seasonal nature of pyramid construction itself, which relied heavily on agricultural laborers available primarily during the inundation months.

A port that functioned only during part of the year would therefore not have posed a logistical problem. On the contrary, it would have matched the rhythm of the labor force and the natural environment in which the pyramid builders worked.

4. Reading the Diary of Merer

In examining the transport of stone to Khufu's harbor, it was essential to consult the primary source known as the Diary of Merer. I therefore obtained and read the 2017 IFAO edition in its entirety.

My initial impression, however, was that the editor, Pierre Tallet, approached the text with strong prior assumptions. His identification of the toponym as "Tura," and several of his interpretive choices, struck me as more definitive than the evidence strictly allows for a corpus of logographic writing. For this reason, I set aside Tallet's translation and commentary and undertook a careful, independent reading of the hieratic text itself.

The surviving material is divided into what are conventionally called Papyrus A and Papyrus B, each accompanied by smaller associated fragments. The two papyri differ significantly in structure and are not parts of a single continuous document.

This is something of a tangent, but it may be worth noting the

following. Tallet's own line-by-line reading of these two documents—the diary proper—contains no reference to a "13th cattle count" or to any regnal year. Although one occasionally encounters the claim online that "Merer's diary records Year 27 of Khufu," this dating appears only in the Conclusions of the 2017 IFAO edition, introduced abruptly and without citation or supporting figure. The Conclusions do mention that the excavated batch included numerous other fragments beyond Papyri A and B, which may lend the figure a superficial plausibility; but no specific source document is identified, nor is any accompanying illustration provided (see Column 4 for a broader critique of how such numbers are converted into regnal years).

As far as I could determine, the diary contains no description of navigation itself, nor any concrete details about the boats. It reads less like a log of voyages and more like a daily record of harbor operations—loading, unloading, and preparations for departure. The verb for sailing ( ) does not appear; instead, the sign for a stationary boat ( ) is consistently used.

Nevertheless, the diary records harbor work at two different locations within the same day, indicating short-distance transport. Even if the document does not describe the transport of Tura limestone, it remains highly informative for understanding how such transport might have been organized. My purpose here is not to evaluate the diary itself, but to note that several aspects of its interpretation warrant further scrutiny.

Ultimately, the diary does not provide direct information about the waterborne transport of stone. However, it does record three destinations at Giza:

("Akhet-Khufu," the Horizon of Khufu)

("the Basin of Khufu")

("the Entrance to the Basin of Khufu")

These references, together with the operational context implied by the diary, suggest a harbor system staffed not only by overseers like Merer, responsible for cargo handling, but also by sailors, administrative officials

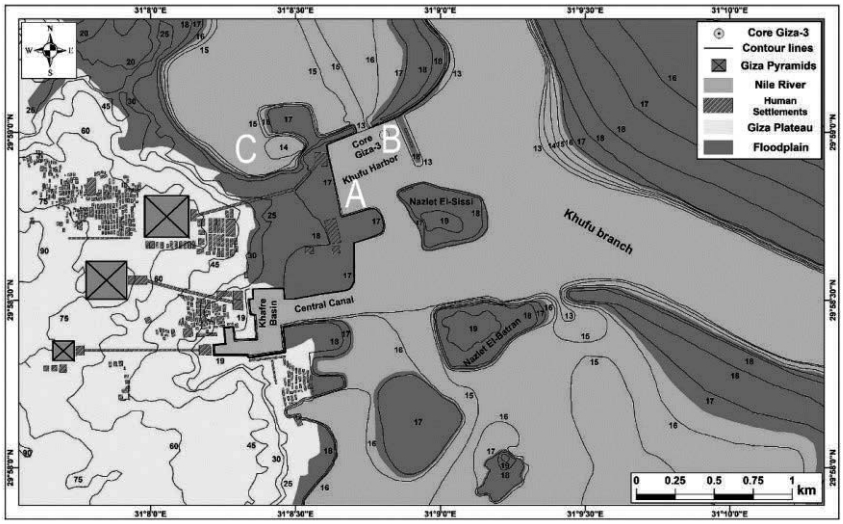


Fig. 4-7. Hypothetical reconstruction of the Giza harbor locations mentioned in the Diary of Merer

managing inventories, and personnel responsible for maintaining the harbor infrastructure.

The text thus offers a glimpse—though a faint one—into a highly differentiated bureaucratic apparatus.

Using the map shown in Fig. 4-7, I propose the following identifications for the three locations mentioned in the diary:

"the Horizon of Khufu"

The presence of the Horus falcon before the toponym indicates a royal installation. Papyrus A1 suggests that this facility was already in operation just before the onset of the inundation. This evokes an image of a dredged, quay-like harbor structure—effectively the ceremonial and administrative "front entrance" to the Giza complex. I identify this with point A on the map, near the Old Kingdom monuments.

"the Basin of Khufu"

I associate this with point C. Whether "basin" or "lake" is immaterial: the location becomes a dry depression during low water and a navigable basin during the inundation. When flooded, it would have been the

closest possible landing point to Khufu's Pyramid for shallow-draft vessels. Its function as a harbor, however, was limited to the flood season. "the Entrance to the Basin of Khufu"

If C is the basin, then the "entrance" must correspond to point B, the area where the main Khufu Harbor quay meets the channel leading into the basin. A and B would have been usable even during low water, while B's quay could have accommodated deeper-draft vessels during the inundation.

Taken together, these identifications suggest that Khufu's harbor system consisted of three functional tiers:

A—the administrative and ceremonial gateway

B—the main, nearly year-round harbor

C—an inner harbor usable only during the inundation

5. Operational Logistics of Supplying the Giza Plateau

The construction of the pyramids required not only Tura limestone but also a vast quantity of additional materials—food, rope, timber, tools, and other consumables. These supplies must have been transported continuously to Giza.

Large, deep-draft vessels carrying heavy granite blocks from Aswan may well have unloaded at point B, the main quay. Even during the agricultural season, when many laborers left Giza, the delivery of supplies would have continued, and both A and B would have remained in use.

The transport of Tura limestone, however, followed a different logic.

Casing-stone transport was not uniform throughout the year; it would have peaked during the inundation, when the largest labor force was available. These stones were relatively small—typically one to three tons. Tura lies only about ten kilometers upstream from Giza, and the blocks could drift downstream with the current.

Given the short distance, modest block size, and the need for high throughput, it is likely that transport relied on numerous small vessels operating in parallel, rather than a few large ships. A piston-shuttle

system would have maximized efficiency.

Loading stone onto a vessel moored broadside to a quay is difficult without cranes. In modern settings, cranes lower loads vertically, but without such equipment, loading must occur from the side. This causes the hull to roll as the weight shifts, making the operation unexpectedly hazardous.

Shallow-draft flat-bottomed boats or papyrus rafts behave differently. Instead of mooring alongside a quay, they drive their bows directly into the shallows, grounding themselves like modern landing craft. Workers on shore can then pull the bow slightly farther onto the bank. In this semi-beached position, the vessel becomes extremely stable, making the loading and unloading of stone far easier.

Fig. 4-8 illustrates this model. On the left, small vessels drift downstream from Tura to Giza, carried by the Nile's current. The river flows at roughly one meter per second, increasing to about 1.5 m/s during the inundation. The journey from Tura to Giza would have taken only two to three hours.

The return trip required sailing upstream, but northerly winds blow along the Nile for most of the year, especially during summer. Thus, the upstream voyage to Tura would have been accomplished primarily under sail.

In such a system, there would have been no need for a transport overseer to accompany the cargo. Loading at Tura and unloading at the

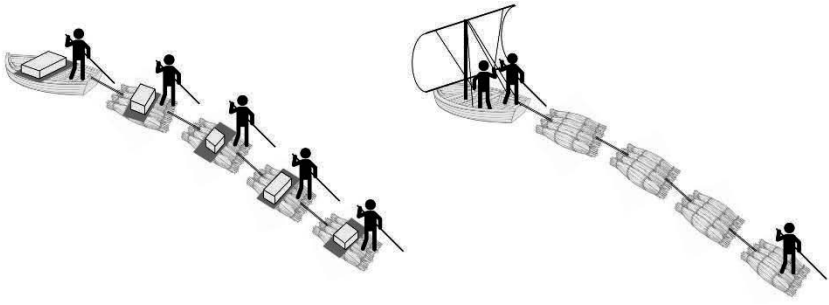


Fig. 4-8. Conceptual model of stone transport using small boats and rafts

Basin of Khufu could have been handled entirely by personnel stationed at each landing site.

I further propose that the fleet operated on a fully divided-labor model. Rather than waiting for unloading to finish, crews of unloaded vessels would immediately sail upstream, while other vessels—already loaded at Tura—would depart downstream toward Giza. This continuous cycle of loading, sailing, and unloading would have maximized throughput. Under such a system, a round trip between Tura and Giza could easily have been completed within a single day.

Notably, no harbor structures comparable to Khufu's harbor have been identified at Tura. This absence supports the idea that casing stones were not loaded onto deep-draft ships but onto shallow-draft vessels that simply ran aground on the riverbank.

Khufu's Pyramid required roughly 100,000 casing stones. Although this number is far smaller than the 2.3 million core blocks, it still implies a peak transport rate of perhaps 50 to 100 stones per day.

Achieving such throughput would have been far easier with many small vessels than with a few large ones. Small craft can be loaded and unloaded quickly, operate in parallel, and require minimal infrastructure.

For these reasons, I believe that the transport of Tura limestone relied on a high-frequency shuttle system of shallow-draft boats and rafts, rather than on large cargo ships.

6. Rethinking the Departure Point in Merer's Diary

Before concluding this chapter, one further point deserves emphasis.

Merer's diary has long been interpreted primarily as a record of transporting casing stones from Tura to Giza. Yet Giza was not only a construction site—it was also a massive consumption center.

The Giza plateau could supply only mudbrick materials and local limestone for core blocks. Everything else—food, timber, rope, tools, consumables, replacement personnel, and administrative supplies—had to be brought in continuously from outside.

If we focus solely on stone transport, we risk overlooking this vast supply network.

In this context, the question of the departure point becomes crucial. Tura was a quarry, nothing more—it could not have served as a supply hub for food, timber, rope, or tools. If Merer's diary records something broader than stone transport, the departure point must lie elsewhere.

The signs and may indicate not merely a waterside location but rather an important urban center—possibly a major administrative or logistical hub. Instead of a simple quarry landing, it may have been a significant city that functioned as a supply base for the entire Giza complex.

If so, the issue extends far beyond whether Merer transported casing stones from Tura. It becomes a question about the broader supply system of the Fourth Dynasty, and about the structure of the Nile transport network itself.

Based on the descriptions in Merer's diary, I suspect that this place name should be sought somewhere south of Tura, yet not as far as Meidum, given the recorded sailing speeds. It seems more plausible that the location lay within the vicinity of Memphis, Saqqara, or Dahshur, rather than at Tura itself.

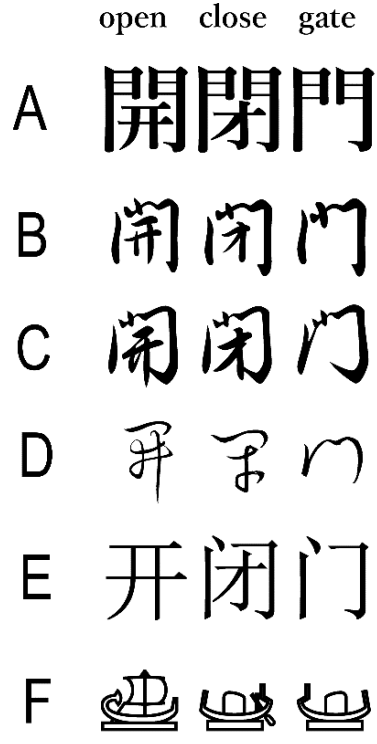
In any case, the first step must be to re-examine the toponym itself, and to identify its true location.

Column 3: A Perspective from a Japanese Reader of Logographic Scripts with 2,000 Years of Tradition

As a Japanese reader accustomed to using Chinese characters—logographic symbols whose origins lie in ancient pictographs—for nearly two millennia, I would like to offer a few observations relevant to the interpretation of Egyptian hieroglyphs.

Figures A–D on the right illustrate the Chinese characters for "open," "close," and "gate." The characters for "open" (開) and "close" (閉) are semantic compounds derived from the character for "gate" (門).

Figures B and C represent gyōshotai (semi-cursive script), a style derived from brush writing. Although individual handwriting varies, calligraphic conventions are strict: even when the "gate" component is heavily simplified, the semantic element indicating "open" is never omitted. To do so would produce an entirely different character.



For example, 開店 means "to open a shop," whereas 門店—if it existed—would mean "a shop that sells gates," which is nonsensical. The meaning collapses if the semantic component is removed.

Figure D shows sōshotai (cursive script), in which the character for "gate" is drastically simplified, yet the semantic element indicating "open" is still preserved. In Chinese simplified characters (Fig. E), the process of reduction goes further:

閉 and 門 resemble their semi-cursive forms, and 開 has been merged with 开, originally a distinct character. Even so, the semantic distinction remains clear enough for communication.

Now consider Fig. F, the Egyptian boat hieroglyphs (upstream travel), (downstream travel), and (stationary boat).

In the Diary of Merer, only the stationary-boat sign appears; the upstream-sailing and downstream-travel signs do not. Tallet's interpretation effectively collapses all three into the stationary-boat sign, but this is problematic. The signs and encode directional meaning:
represents upstream travel under sail,
represents downstream travel using an oar for steering.

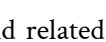
These forms reflect the environmental reality of Egypt, where northerly winds allowed upstream sailing, while downstream travel relied on drifting with the current and steering with an oar.

In a logographic writing system, using the same sign regardless of direction would be equivalent to writing "open" and "gate" with the same character—an error not merely of spelling but of semantic category.

The sign , by contrast, denotes a stationary boat, not the action of traveling upstream or downstream. This distinction parallels the difference between "open/close" (actions) and "gate" (an object).

To illustrate the linguistic point: in Japanese, "to go upstream," "to go downstream," and "boat" are entirely different words—noboru, kudaru, and fune. It would be inconceivable to write them with the same character simply because the shapes resemble one another. Likewise, it is implausible that ancient Egyptian scribes would confuse , , and , which represent different actions and likely different phonetic values.

Georg Möller's Hieratische Paläographie (vol. 1) includes hieratic forms of and . As I anticipated, the hieratic form of clearly shows a diagonal, paddle-like stroke. The form of in Merer's diary closely resembles the variant circled in Möller's table.

Faulkner's dictionary lists with the meaning "expedition," and with the meaning "to cross the river," suggesting a semantic field related to movement or passage. However, 

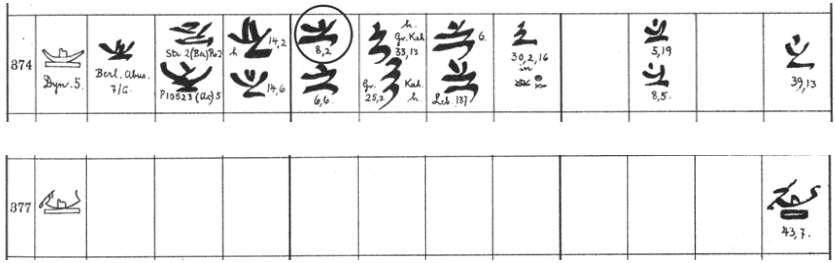


Fig. C2-1. Excerpt from Georg Möller, Hieratische Paläographie, Band I. Annotated by the author (circled marks).Courtesy of the General Library, The University of Tokyo. CC BY.

does not appear. This absence is not decisive.

In modern lexicography, specialized terms often fail to appear in general dictionaries.

For example, anchorage ground is a standard maritime term, yet many general dictionaries omit it; meanwhile, Anchorage appears widely as the name of a city in Alaska. No one would interpret anchorage ground in a maritime document as referring to a baseball field in Anchorage.

Context and domain determine meaning.

Ancient Egyptian dictionaries are far from complete; they cannot be treated as exhaustive inventories of all possible words. The absence of a term from a dictionary does not prove that the term did not exist.

Given that Merer's work clearly involved harbor operations, it is reasonable to assume that in his diary refers to a technical term specific to port work—loading, unloading, or preparing a vessel while stationary. Words for "expedition" or "crossing the river" belong to the vocabulary of passengers, not harbor workers. Expecting specialized port terminology to appear in general dictionaries is unrealistic.

Traditional Egyptology often proceeds by phonetic transcription before semantic interpretation.

From the perspective of someone accustomed to logographic systems, this approach risks overlooking the visual logic of the script. In my view, scholars working with hieroglyphs would benefit from consulting

specialists in Chinese or Japanese calligraphy—people trained in the rules governing which parts of a logographic character may be simplified and which must be preserved.

For those who have not lived within a logographic writing culture, intuitively understanding the permissible ways to "deform" a character is extremely difficult.

CHAPTER 5

Rethinking the Construction Slopes of the True Pyramid

1. The Step Pyramid of the Third Dynasty and the Problem of Construction Slopes

The literature on pyramid construction contains a vast number of hypotheses concerning the ramps used to transport stone. Yet before discussing the geometry of any ramp system, one must address a more fundamental issue: the provision of adequate working space for masonry. Many earlier theories, in my view, fail precisely because they overlook this essential requirement.

Fig. 5-1. The Step Pyramid of King Djoser (photographed in 2008).
The two tourists visible at the lower right are standing considerably closer to the camera than the monument itself; the actual height of the pyramid is 62 m.

Let us begin with the Step Pyramid of the Third Dynasty, which is often assumed—intuitively but incorrectly—to provide natural working terraces simply because of its stepped form. It is true that each step forms a terrace roughly ten meters wide. However, the very name "step pyramid" is misleading. Although the monument appears stepped from a distance, it rises to a height of 62 meters and consists of six stages. Each stage is therefore approximately ten meters high, with some exceeding that height. Seen up close, each "step" is not a stair but a sheer cliff face.

The masonry of the Step Pyramid consists of inward-leaning blocks approximately 25 cm high and 30–80 cm wide. Because inward-leaning masonry is built from the center outward, the outermost face is completed last. To place stones on an exterior face ten meters above the terrace below, workers would have required scaffolding, not merely a ramp. In other words, a ramp alone could not have provided the working platform necessary for setting the outer stones.

Fig. 5-2. Remains of the ancient mudbrick scaffolding preserved on the rear side of the First Pylon at Karnak (photographed in 2008).
The mudbrick retaining wall in the foreground is likely a modern intervention intended to prevent ancient bricks from collapsing onto the tourist pathway.

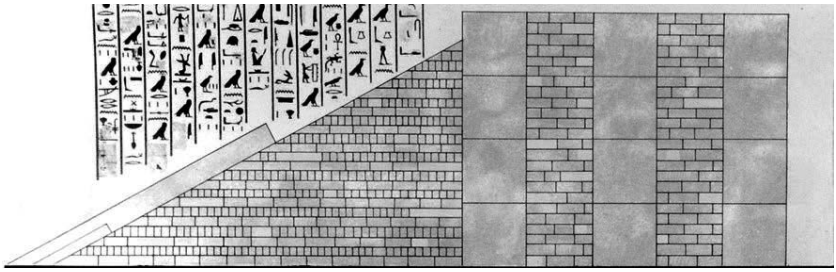


Fig. 5-3. Mudbrick construction ramp depicted in a wall painting. (After Karl Richard Lepsius, Denkmäler aus Aegypten und Aethiopien, 1849–1859, Abteilung III, Blatt 40.)

When I visited the site in 2008, scaffolding for restoration work had indeed been erected along the stepped faces. The ten-meter terraces contribute useful space for constructing such scaffolding, but the scaffolding itself must surround the exterior of the masonry core. The terraces alone do not eliminate the need for it.

As noted in Chapter 1, ancient Egyptian builders preferred mudbrick scaffolding over wooden frameworks. Mudbrick was easier to produce, and for supporting the placement of heavy stone blocks, it provided a far more stable structure. Large quantities of mudbrick debris have been recorded at unfinished Third Dynasty pyramids, and although from a later period, the rear of the First Pylon at Karnak still preserves mudbrick scaffolding from an abandoned construction phase. These examples strongly suggest that mudbrick scaffolding was the standard method for creating elevated working platforms.

A similar example—also from the New Kingdom—appears in the tomb of Rekhmire at Luxor, where a wall painting depicts the construction of a mudbrick ramp. What struck me as particularly fascinating is that the method of laying the bricks in this relief is identical to the technique used in the modern mudbrick retaining wall shown earlier in Fig. 5-2, which was likely built in recent years to prevent ancient bricks from collapsing onto the tourist pathway.

The continuity is remarkable: even after 2,500 years, mudbrick has

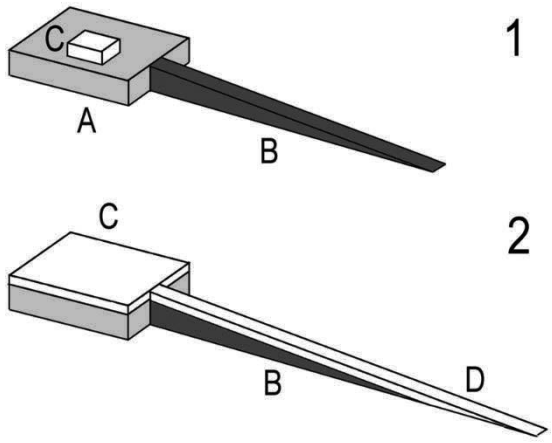


Fig. 5-4. Conceptual diagram of a simple construction ramp.

survived as a viable construction material, and the technique of laying it has remained essentially unchanged. This persistence of both material and method left a strong impression on me.

Among the many hypotheses proposed for pyramid-construction ramps, the most straightforward is the single, linear ramp. Such simple ramps were in fact built in antiquity, and traces of a straight ramp connecting the Giza Plateau to the Nile riverbank have been identified archaeologically.

However, for a structure like a pyramid—whose height increases continuously as construction progresses—a simple ramp soon encounters practical limitations.

In Fig. 5-4 (1), ramp B is shown delivering stone to construct structure C atop foundation A. Once C is completed and work begins on the next level, the ramp must be extended upward to match the new height. This produces ramp D, essentially an enlargement of B.

In Fig. 5-4 (2), the slope angle has been kept constant for clarity, resulting in a dramatically lengthened ramp. In reality, the builders may have increased the gradient to prevent the ramp from becoming excessively long. Even so, raising the ramp each time the pyramid grew taller would have been a major construction project in its own right.

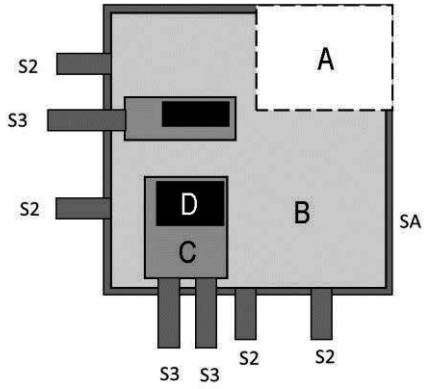


Fig. 5-5. Simple ramp in early construction phase.

That said, during the earliest stages of pyramid construction—when the structure was only about ten meters high—the required ramp length would not have been prohibitive. Because the lower courses of a pyramid require the greatest volume of stone, constructing multiple simple ramps or a single, very wide ramp for high-throughput transport would have been entirely rational in the initial phase of building.

Fig. 5-5 illustrates a hypothetical scenario in which a simple linear ramp is employed during the earliest stages of pyramid construction. In this diagram, A represents the area where the bedrock is still being leveled in preparation for the first course; B, C, and D correspond to the masonry of the first, second, and third courses, respectively. S1 denotes the scaffolding for casing-stone installation, while S2 and S3 represent the ramps used for work on the second and third courses.

This arrangement offers a significant advantage: provided that a sufficient stockpile of stone has been secured in advance, the first three courses can be built in parallel. For the lower levels of a pyramid—where the base area is large and the volume of stone required is greatest—such parallelization may have been an effective means of shortening the overall construction time.

A practical method for preventing a straight ramp from becoming excessively long is the use of a switchback ramp, or zigzag ramp. This is

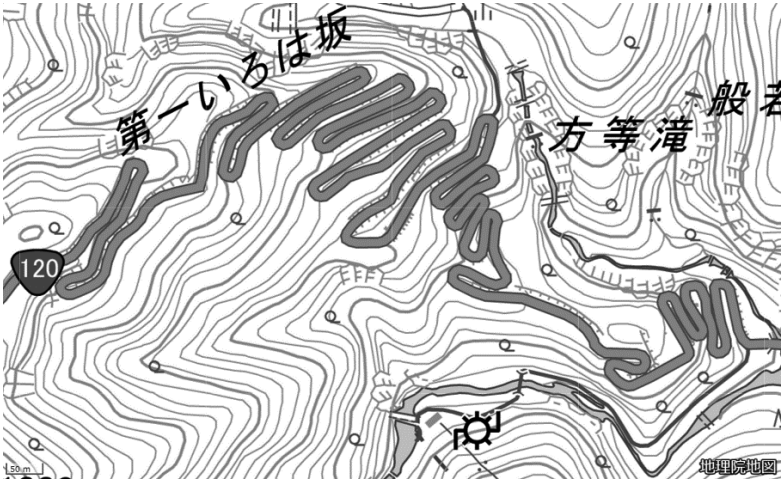


Fig. 5-6. The First Irohazaka Road in Nikko, a classic example of a hairpin (switchback) mountain road, as shown on a GSI topographic map. (Geospatial Information Authority of Japan)

the same principle employed in mountain roads that climb steep passes—Japan's Irohazaka at Nikkō is a well-known example. When space is limited yet a gentle gradient must be maintained, the switchback configuration provides an effective solution.

Other proposals include constructing radial ramps, but a common shortcoming of most traditional ramp theories is that they fail to consider the working space required for setting the outer masonry. The scaffolding needed for masonry work and the ramps used for transporting stone must be conceived as separate structures.

However—and this, I believe, reflects the very design philosophy behind the Step Pyramid—the terraces of the monument are approximately ten meters wide. Even if five meters are allocated to working scaffolds (shown in black), an additional five meters remain unused. This remaining width could easily have accommodated a ramp ascending from one terrace to the next (shown in white).

In such a configuration, the scaffolding and the ramp could be constructed simultaneously, making the system highly efficient. There

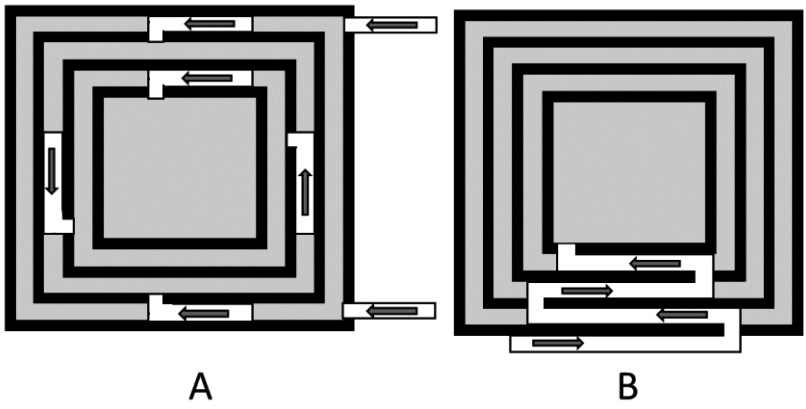


Fig. 5-7. Plan view illustrating how the terraces of the Step Pyramid could have been used to construct switchback ramps on each level.

would have been no need to build a massive, independent ramp like the one illustrated in Fig. 5-7; the surplus terrace space itself could function as the foundation for the ramp. The design freedom for such ramps is considerable, and multiple configurations are conceivable.

Fig. 5-7B presents one such possibility: a switchback (zigzag) ramp constructed along the terraces.

2. Conditions Differ in the True Pyramid

King Sneferu, founder of the Fourth Dynasty, transformed the Step Pyramid at Meidum into a true pyramid by adding masonry to its exterior. In a step pyramid, the terraces allow the simultaneous construction of scaffolding and ramps, but a true pyramid presents a fundamentally different situation: its exterior forms a continuous inclined surface, and the terrace structure no longer exists. Surprisingly, this crucial distinction has rarely been acknowledged in earlier scholarship. Technically speaking, the true pyramid is not a simple extension of the step-pyramid system; its scaffolding and ramp arrangements required an entirely new conceptual approach.

When Sneferu began the conversion, any scaffolding or ramps

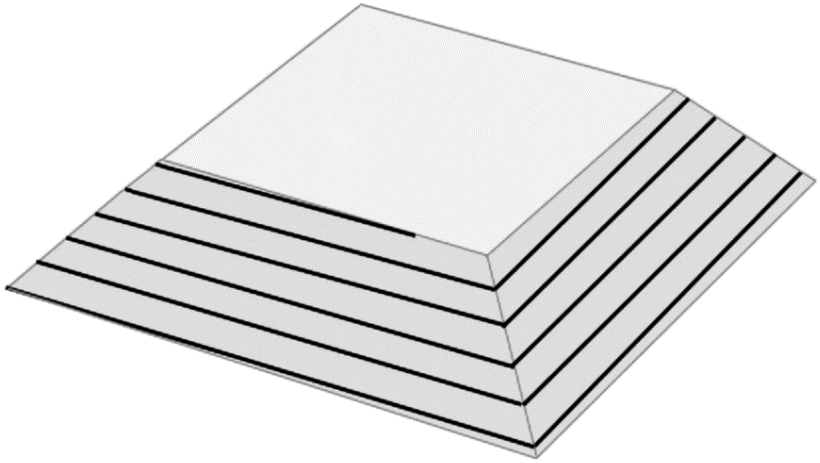


Fig. 5-8. Conceptual illustration of the double-helix loop: mudbrick scaffolding constructed around the outer casing of the pyramid, with a circumferential ramp built around the exterior of the scaffolding.

remaining on the terraces of the original step pyramid would have obstructed the new work. It is therefore reasonable to assume that the earlier installations were dismantled and replaced with new scaffolding and ramps designed specifically for the true-pyramid form.

A key point is that the true pyramid required the placement of casing stones along its outer surface, and these had to be set only after the internal masonry beneath them was complete. Consequently, peripheral scaffolding was indispensable.

If mudbrick scaffolding had already been standard practice during the construction of step pyramids, then erecting scaffolding around the growing mass of the pyramid would not have been an extraordinary task. The real challenge lay in determining how to construct the ramps in coordination with the scaffolding.

As noted earlier, building the scaffolding and the ramp in tandem is highly efficient. One plausible solution is the system illustrated in Fig. 5-8: a spiral ramp encircling the pyramid, built along the outer face of the mudbrick scaffolding. Because this structure consists of a dual system—

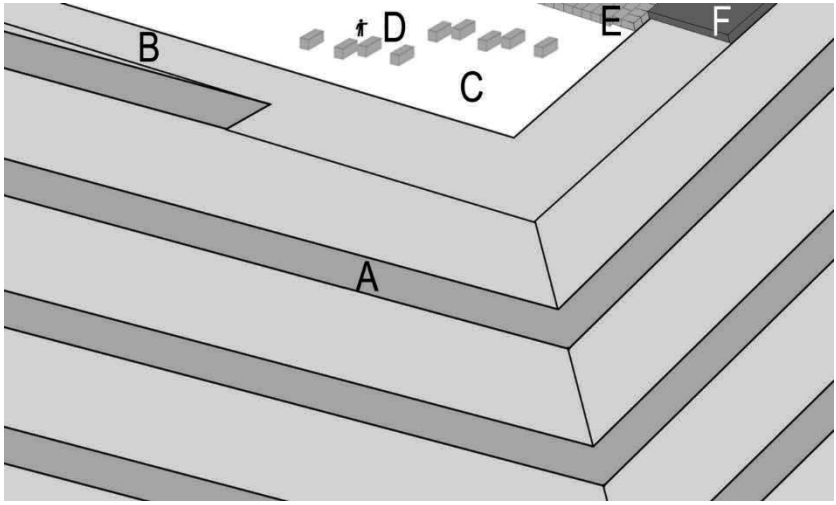


Fig. 5-9. Enlarged view of the terminal section of the double-helix loop.

scaffolding plus a circulation path—I refer to it as a double-helix loop.

Fig. 5-9 presents an enlarged conceptual view of the terminal section of the double-helix loop. In this example, the circumferential ramp (A) is five meters wide, and the working scaffold (B) is likewise five meters wide. At the stage shown here—before the ramp has been constructed—the scaffold temporarily occupies the full ten-meter width of the terrace.

Surface C represents the completed masonry face, which functions as the active construction zone. The diagram makes clear that the foundations of both the scaffold and the ramp wrap around the exterior of the pyramid, forming a continuous envelope of mudbrick.

The human figures and stone blocks labeled D are included to provide a sense of scale, making it intuitively apparent that the quantity of mudbrick required for both the scaffold and the ramp would have been immense.

Area E shows the pyramid after the masonry and casing stones have been fully completed. With the casing in place, the mudbrick structures used for scaffolding and ramping are removed, as indicated at F.

Fig. 5-10. Exposed section of the Bent Pyramid showing the matched heights of core masonry and casing stones, as well as the contrast between the rough-finished core blocks and the finely cut, inward-leaning casing.

Fig. 5-11. Lowest course of the Pyramid of Menkaure, showing the use of red granite: the upper and lower faces are finely dressed, while the exterior faces remain rough-finished with pronounced irregularities.

Examination of the collapsed casing zones of the Bent Pyramid shows that the heights of the casing stones and the core blocks are precisely matched. The same is true at the Pyramid of Menkaure: although the exterior faces of the granite casing blocks remain in a rough, unfinished state, their upper and lower faces are accurately dressed so that their height corresponds exactly to that of the adjacent core masonry.

However, as noted in Column 1 on p. 33, the course heights of pyramid masonry are not uniform. This fact strongly indicates that the casing stones for each course were installed immediately after the core blocks of that course were set. In other words, the construction sequence required the casing to be placed in close synchrony with the core masonry.

Some earlier theories of pyramid construction have proposed that the installation of core blocks and casing stones constituted separate operations. Yet, with the exception of the Meidum pyramid—where a completed step pyramid was later converted into a true pyramid—the monuments of the Fourth Dynasty, from the Bent Pyramid at Dahshur to the Pyramid of Menkaure at Giza, consistently show identical course heights in both core and casing. This provides strong evidence that the casing stones were installed immediately following the completion of each corresponding core course.

Although pyramids of the Fifth Dynasty and later sometimes exhibit discrepancies between the dimensions of core and casing stones, the present discussion concerns the Fourth Dynasty, where the evidence overwhelmingly supports the conclusion that casing installation proceeded in step with the core masonry. The analysis that follows therefore adopts this synchronized construction process as a working premise.

Fig. 5-12 presents a conceptual view of masonry work being carried out on the double-helix loop.

Element A represents the already-set core blocks, and B the casing stones that have been installed. In this stage, the outer faces of the casing stones (B) remain in a rough-finished state, but all other faces are accurately dressed so that the stones fit tightly together. Area C marks the

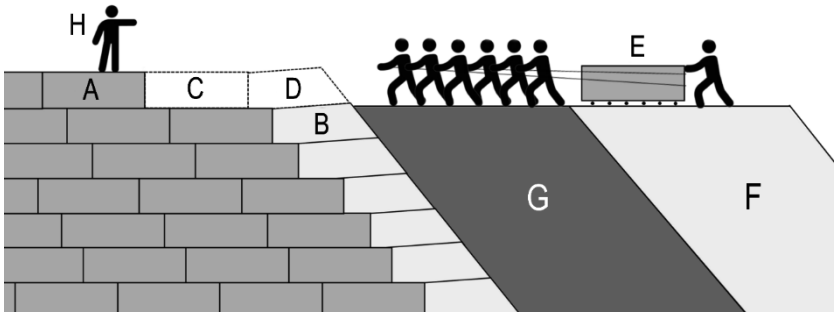


Fig. 5-12. Conceptual view of a pyramid masonry worksite.

location where the next stone (E) will be placed, and D indicates the position where the casing stone will be installed after C has been completed. The ramp is shown as F, and the working scaffold as G. H represents the overseer directing the work.

Although the exterior faces of the casing stones must ultimately be polished to a high degree of precision—as seen in the casing of the Bent Pyramid in Fig. 5-10—this finishing process would have been carried out only after the masonry had reached the summit and the mudbrick scaffolding and ramps were removed progressively from the top downward. Thus, during the active construction phase, both the core blocks and the casing stones would have remained in a rough-finished state, much like the granite casing of the Pyramid of Menkaure shown in Fig. 5-11.

3. Difficulties with the Timber-Scaffolding Hypothesis

Many readers may wonder why such massive mudbrick scaffolding is necessary at all, and may feel that a simple timber framework would suffice. This impression likely stems from popular books on pyramid construction, which frequently depict scenes like Fig. 5-13A, showing a fully formed wooden scaffold.

It was precisely such illustrations that first led me to question the traditional timber-scaffolding hypothesis. Most drawings present only

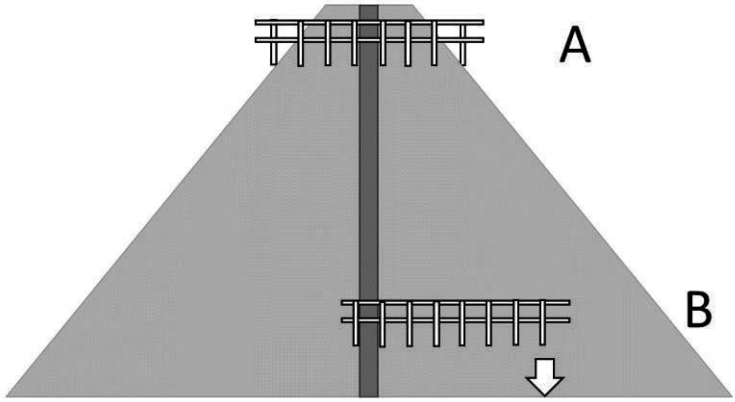


Fig. 5-13. Impracticality of constructing pyramid scaffolding using timber.

the completed structure, as in A. In that idealized state—and using modern materials and techniques—such a scaffold is not entirely impossible: one could assemble a rigid steel-pipe frame on the ground, using proper joints and diagonal bracing, then lift the entire structure by helicopter or crane and lower it into place from above. Even on an unstable slope, a sufficiently rigid steel frame could theoretically withstand the loads.

However, this is not how such scaffolding would be built in reality. The actual construction process would require the scaffold to be extended outward cantilevered, as shown in B—and this method is considered impractical even today. The casing stones of a pyramid provide no footholds for supporting the legs of a scaffold. Extending a timber or pipe structure outward in a cantilevered fashion would impose severe torsional loads at the base. Extending such a structure tens of meters horizontally is simply unrealistic, even with modern engineering.

Some illustrators may have assumed that if the final image looks plausible, the construction process must also be feasible. Others may have realized that the process depicted in B is impossible, yet chose not to draw it—preferring silence over acknowledging the inconvenient truth.

When encountering diagrams like A, one should examine carefully how the base of the scaffold is fixed to the sloping surface, and then

imagine the actual construction sequence. It quickly becomes apparent that such scaffolding cannot be built in reality.

The French architect Jean-Pierre Houdin proposed an internal-ramp theory in 2007 with support from Dassault Systèmes. I do not find this convincing. While the concept may function within a 3D model or theoretical framework, I cannot see how it could sustain a throughput of 500 blocks per day, which is required for real pyramid construction. Moreover, Houdin assumes that casing stones were polished before installation, yet surviving examples contradict this: the Bent Pyramid shows extremely precise finished surfaces, whereas the Pyramid of Menkaure preserves casing stones in a rough-finished state. These observations do not align with his proposed method.

Lighting and ventilation within an internal ramp would also pose serious challenges. I cannot form a plausible mental image of such a system functioning in practice. My concern is not whether a single block could be moved this way, but whether such a method could sustain the daily transport and placement of hundreds of blocks for more than a decade.

4. Sun-Dried Mudbrick for Ramp Construction

It is intuitively clear that constructing not only the ramps but also the working scaffolds from sun-dried mudbrick would have required an enormous quantity of material. To verify this, I carried out a numerical estimate.

The volume V of a truncated square pyramid with upper sides a,, lower sides A,B, and height h is given by:

$$V=h(Ab+aB+2(ab+AB))/6$$

In the case of the Great Pyramid of Khufu, the uppermost masonry has been lost, but the base length is 230 m and the design height is estimated at 146.6 m. If we assume a pyramidion 1 m high with a 1 m square base, then a=b=1 m, A=B=230 m, and the height of the main body becomes

145.6 m. The resulting volume of the pyramid excluding the pyramidion is: 2,578,755 m^3.

If we assume that a 5-m-wide scaffold enveloped the pyramid, the volume of the truncated pyramid including the scaffold becomes 2,917,853 m^3, meaning that the scaffold alone accounts for: 339,098 m^3.

Adding a 5-m-wide ramp around the exterior yields a ramp volume of 188,620 m^3; if the ramp width is increased to 10 m, the volume rises to 392,620 m^3. In the early stages of construction, when the working area per course is large, a 5-m-wide transport path may have been insufficient. However, there is no compelling reason to assume that a 10-m-wide ramp was required all the way to the top. It is more plausible that the ramp gradually narrowed as construction progressed upward.

One exception must be considered: the transport of the massive granite beams used in the ceiling of the King's Chamber. According to Perring's measurements, if the pyramid's height is taken as 146.6 m, the ceiling of the King's Chamber lies at approximately 47 m, or 32% of the total height. The uppermost gabled stones of the stress-relieving structure lie at about 43% of the total height. To transport such enormous beams, a 10-m-wide ramp would have been reasonable at least up to this level.

For these reasons, I adopt the working assumption that Khufu's pyramid required approximately:

340,000 m^3 of mudbrick for scaffolding

340,000 m^3 for ramps

for a total of 680,000 m^3.

In Chapter 1, I assumed a standard mudbrick size of 30 cm × 15 cm × 10 cm, giving a volume of 0.0045 m^3 per brick. Thus, 680,000 m^3 corresponds to: 151 million bricks.

This is an enormous number, but not unmanageable for a state-organized project. If one worker produced 100 bricks per day, then 1,000 workers could produce 100,000 bricks daily. Even limiting production to the seven months of the low-water season, annual output would reach 21 million bricks. At that rate, producing 151 million bricks would require less than eight years, which does not conflict with the

overall construction timeline of the pyramid.

The more serious issue is not the labor of brickmaking but the source of the raw material—the Nile silt deposited by annual inundation. I initially assumed, mistakenly, that the flood would deposit large quantities of fertile soil each year. In reality, the annual deposition is only a few millimeters to a few centimeters. This means that the material removed does not naturally replenish itself at a rate sufficient for large-scale extraction.

When considering where the enormous quantity of mud—680,000 m^3—required for the ramps and scaffolding could have been obtained at Giza, the answer becomes apparent upon examining Khufu Harbor and Khufu Lake.

The lake extends roughly one kilometer east to west, and the contrast in contour-line spacing between its western and eastern sides is striking. What would originally have been a gentle slope, forming a basin during the low-water season, now appears more like the remnant of open-pit extraction, as if large quantities of mud had been quarried from it.

Khufu Harbor itself also shows signs of artificial dredging. This raises an important question: what became of the excavated spoil? Even in

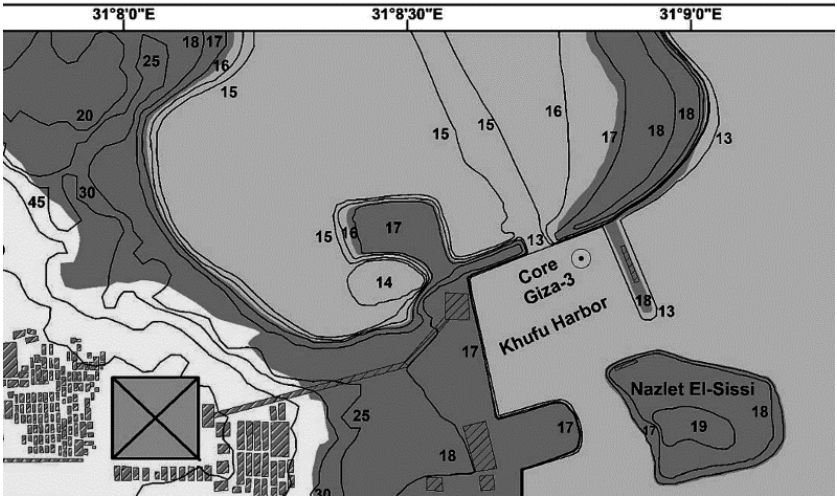


Fig. 5-14. Topography and contour lines of Khufu Harbor and Khufu Lake.

modern civil engineering, the primary challenge is often not the excavation itself—easily accomplished with heavy machinery—but the logistics of spoil disposal. Construction cannot proceed unless a clear plan exists for transporting and depositing the removed material.

Viewed from this perspective, the evidence strongly suggests that:
extraction of mud for sun-dried bricks,
dredging of Khufu Harbor,
excavation of Khufu Lake
were not independent activities. Rather, they appear to have been components of a single, integrated engineering project, planned from the outset as mutually reinforcing operations.

5. Corner Sections of the Circumferential Ramp

By its very nature, a circumferential ramp must turn at nearly right angles at each corner. Whether one attempts to negotiate the curve using rollers or a wooden sledge, significant lateral forces arise, making the maneuver inherently difficult. When workers attempt to turn the load using human pulling force alone, sliding friction develops either between the rollers and the ramp surface or between the rollers and the stone block itself. As a result, the force required to execute the turn becomes far greater than under straight-line motion.

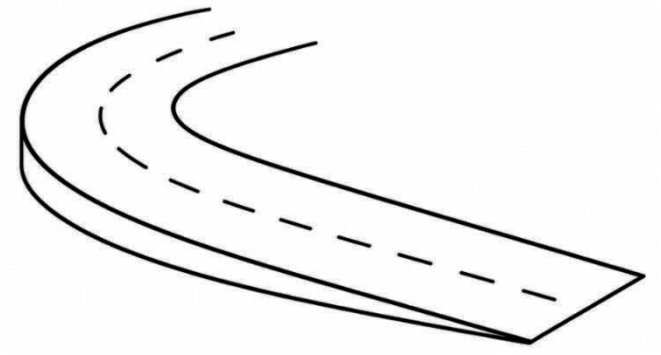


Fig. 5-15. Conceptual illustration of road-curve superelevation (cant).

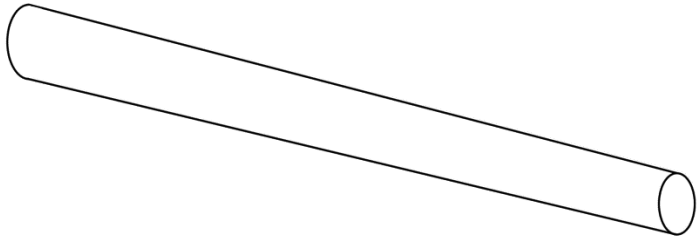


Fig. 5-16. Conceptual illustration of tapered rollers used at ramp corners.

A practical method for reducing these lateral forces is to construct the ramp with a superelevated profile, in which the outer edge is higher and the inner edge lower. This configuration—known as cant—creates a gravitational component that naturally urges the stone inward, making it easier for the load to follow the curve.

Mountain roads with sharp switchbacks employ the same principle: the cant counteracts the outward motion caused by centrifugal force, allowing vehicles to negotiate the curve more safely. The geometry required for the pyramid ramp is analogous.

Another method for facilitating cornering is to shape the rollers themselves as slightly tapered frustums, with the outer side made marginally thicker and the inner side thinner. In such a configuration, the outer circumference travels a longer distance per rotation than the inner circumference, causing the roller to turn naturally toward the inside of the curve.

However, this design inevitably introduces sliding friction and torsional stress within the roller. As a result, the rollers would experience rapid wear. It is therefore likely that tapered rollers were treated as consumable components, intended for short-term use and replaced frequently during operation.

It is also conceivable—though still speculative—that the rollers were divided into two separate units, one for the outer side and one for the inner side. Because these two rollers are not mechanically connected, each can rotate independently, thereby greatly reducing torsional stress.

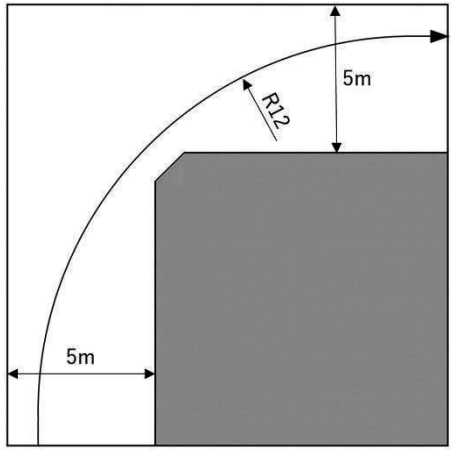


Fig. 5-17. Conceptual view of direction change at a ramp corner.

Although this arrangement would make handling and alignment more complex, the rollers would be easier to transport, and it is possible that such a system was actually employed.

At first glance, one might assume that a 5-meter-wide ramp would require a turning radius of roughly 5 m at each corner. However, even a modest 1-meter chamfer at the inner corner of the scaffold significantly alters the geometry: with this small modification, the load can follow a gentle curve with a radius of approximately 12 m.

Even large core blocks rarely exceed 2 m in length, so a 5-meter-wide ramp would have provided sufficient clearance for the stones to negotiate the corner without difficulty. In practice, the turning radius was therefore far more generous than intuition might suggest, and the circumferential ramp would not have posed an insurmountable obstacle to transporting sizable blocks.

6. Rollers Are Surprisingly Safe on Gentle Slopes

On a gentle slope, it is intuitively easy to understand that stone blocks can be hauled with relatively little effort when rollers are used. At the same time, one might worry that using rollers on a slope could allow a

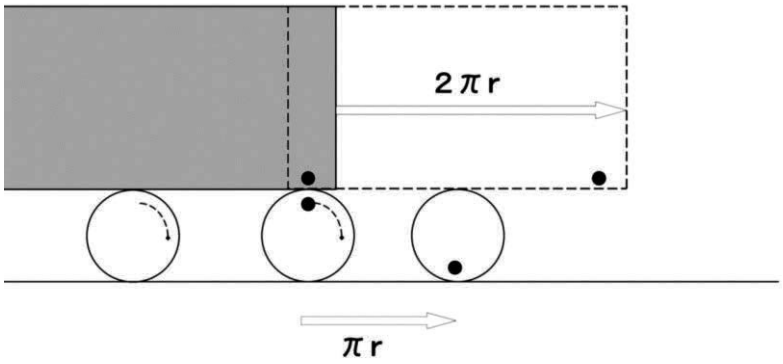


Fig. 5-18. Operation of rollers

block to slip and run uncontrollably downhill due to its own weight. Although such a risk does exist, the operating principle of rollers differs fundamentally from that of wheels, and a block that begins to move downward will not continue accelerating indefinitely.

Fig. 5-18 (reproduced from Fig. 3-6) illustrates the basic mechanics of rollers. When the roller has radius r, the roller advances a distance of πr per rotation, while the stone block advances 2πr. Conversely, if the block has length L, then when the block has moved downward by L, the roller has advanced only L/2. At that point, half of the block has already slipped off the roller, causing one corner of the block to contact the slope surface directly. This contact produces a large frictional force, which brings the block to a stop. Thus, the block cannot continue running downhill indefinitely.

In contrast, when a wooden sledge is used, workers would naturally attempt to reduce static and kinetic friction by spreading sand or water on the ramp surface. On a gentle slope, the block may remain stationary when pulling stops. However, as the slope becomes steeper, the reduced friction means that the block will begin to slide as soon as the pulling force ceases. Once the block overcomes static friction, only kinetic friction remains to resist motion. But the very fact that the block has begun to move indicates that gravity has already exceeded static friction; therefore, kinetic friction is insufficient to stop it. A sliding block will

continue to accelerate, and once it begins to run downhill, it becomes extremely difficult to halt.

In both systems—rollers and sledges—the downslope gravitational component is always present. On steeper slopes, the risk of unintended motion becomes significant the moment pulling stops. For this reason, workers would have needed to employ wedges, functioning like modern wheel chocks, to prevent runaway blocks during transport operations.

7. Considerations on the Method of Setting Stone Blocks

The next issue concerns the final stage of stone transport—how the block was removed from the rollers and placed precisely at its intended position in the masonry. Traditional illustrations often depict workers using levers to maneuver the stone into place. While levering is certainly a plausible method, I wondered whether a more efficient and systematic

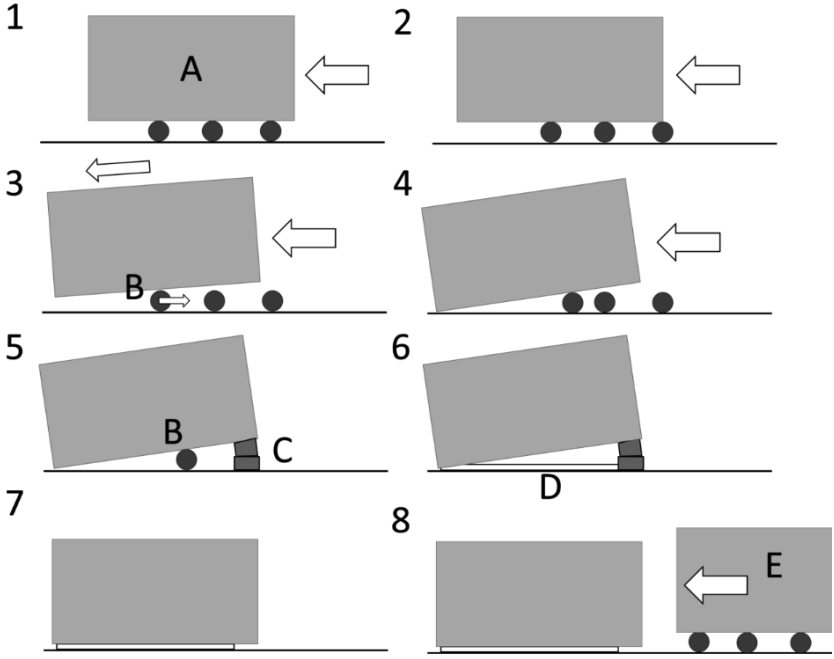


Fig. 5-19. Proposed method for placing a stone block at its designated position.

technique might have been available. This line of thought led to the concept illustrated in Fig. 5-19.

Steps 1–2

Fig. 5-19-1 shows stone block A being transported on rollers. As the block approaches its intended placement site, the workers stop adding new rollers to the front of the path, as shown in Fig. 5-19-2.

Steps 3–4

When block A is pushed forward from behind, its front edge eventually overhangs the last roller and begins to tilt downward under its own weight. As the block continues to move, it pushes the remaining roller B backward. The block finally comes to rest when its front edge contacts the ground surface directly, as illustrated in Fig. 5-19-4.

Step 5

To remove roller B from beneath the block, the workers first place a temporary support C—made of sun-dried mudbrick—under the raised rear end of the block. With the load now transferred to support C, roller B can be removed easily by tapping it lightly or shifting it with a small lever.

Steps 6–7

After removing the roller, the workers fill the gap beneath the block with mortar D, which both reduces friction and fills the joints between stones (Fig. 5-19-6). Water is then poured onto the temporary mudbrick support C.

Sun-dried mudbrick rapidly loses strength when it absorbs water. Under the weight of the block, the brick begins to crack; water penetrates these cracks, accelerating the collapse. Ultimately, the mudbrick reverts to a soft, mud-like state, as shown in Fig. 5-19-7. By adjusting the amount of water applied, workers could precisely control the rate at which the block settled into its final horizontal position. This controllability is the central advantage of the method.

Step 8

Once the block has fully settled, the mortar beneath it has not yet hardened, and friction is still low. This allows workers to perform fine

positional adjustments with minimal effort—for example, by gently pushing the block with the next incoming stone E, as shown in Fig. 5-19-8.

Whether this technique was actually used in pyramid construction cannot be known. It remains a hypothetical possibility, and because the collapse of sun-dried mudbrick leaves no archaeological trace, it is difficult to prove. Nevertheless, given that workers had to place large numbers of blocks every day, it is worth considering whether they relied solely on brute force and simple levers, or whether they developed more efficient, sustainable procedures such as the one proposed here.

8. Examination of the Ramp System of Khufu's Pyramid

To conclude this chapter on ramps, I present the model I have assumed for the ramp system of Khufu's Pyramid.

As a simplifying premise, I assumed that the external circumferential ramp ascended four courses per side of the pyramid. One full circuit would therefore raise the working level by sixteen courses. Since Khufu's Pyramid consists of 203 courses, a ramp rising sixteen courses per circuit would require approximately 12.7 circuits to reach the summit. Under this configuration, the total ramp length would be about 6.2 km.

A rise of four courses per side corresponds, for example, to a height of roughly 1.5 m on the first side. This yields a slope angle of 1.43°, or 2.5% in road-engineering terms. Although extremely gentle, such a slope is still perceptible to humans as a "mild incline" and corresponds to the gradient at which wheelchair users begin to feel increased effort.

The slope angle and total ramp length are in a trade-off relationship, but interestingly, when the ramp is constructed as a circumferential structure, the total volume of sun-dried mudbrick required remains nearly constant whether the slope is steep and short or gentle and long. This is because, as shown in the formula derived in Section 4, the required mudbrick volume does not depend on the number of circuits. With fewer circuits, the inward offset per circuit increases, resulting in a thicker ramp base, which compensates for the reduced length. Thus, the

total material requirement remains nearly unchanged.

From the standpoint of maintaining throughput and ensuring sustainable human labor, a gentle, long ramp reduces the burden on each worker and is therefore preferable.

Although a total length of 6.2 km may seem excessive, the stones were not transported by a single team over the entire distance. By dividing the transport route into multiple segments and assigning each team to a specific section, the workers would not need to traverse the full length. For example, whether four teams each transport stones over the entire 6.2 km or relay them in 1.55 km segments, the theoretical throughput remains nearly identical (excluding handover time). Considering fatigue from prolonged continuous labor, the relay method would likely be more efficient.

At a slope of 2.5%, the downslope gravitational component acting on a 3-ton block is about 75 kgf (2.5% of its weight). On level ground, assuming a rolling resistance coefficient of 0.1, moving a 3-ton block requires 300 kgf, or 150 kgf if rolling resistance is 0.05. Thus, on a 2.5% slope, the required pulling force increases only modestly—about 25% when rolling resistance is 0.1.

This calculation also shows that at a 2.5% gradient, even with an ideal rolling resistance of 0.05, the gravitational component is only half of the rolling resistance force. Therefore, a block will not spontaneously run downhill if workers stop pulling.

As discussed in Chapter 3, a worker pushing a horizontal bar can exert about 20 kgf for short periods, 15 kgf for sustained heavy labor, and 10 kgf comfortably. Under a 2.5% slope with rolling resistance between 0.05 and 0.1, moving a 3-ton block requires 225–375 kgf, meaning 20 workers could accomplish the task. Since level-ground transport required about 16 workers, the increase is minimal. With 20 workers, a transport speed of 2 km/h would likely have been achievable.

In Chapter 2, I noted that constructing Khufu's Pyramid required placing 500 blocks per day, corresponding to a throughput of one block every 1.3 minutes during an 11-hour workday. Even if this throughput

were achieved on level ground, it would be meaningless unless the same rate could be maintained on the pyramid's ramp. To avoid reducing transport speed on the slope, a gentle gradient was essential.

Conversely, if one assumes the 5% or 7% gradients proposed in traditional theories, the downslope gravitational force on a 3-ton block becomes 150 kgf at 5% and 210 kgf at 7%. With a rolling resistance of 0.05, the block would be at risk of sliding downhill uncontrollably. Preventing such runaway motion would require additional safety measures, severely degrading workability. Thus, although steeper slopes shorten the ramp, they are inferior when considering workability, safety, and long-term sustainability. A gentle slope is clearly the superior solution.

CHAPTER 6

Considering the Construction Process of the Pyramid

1. Examination of the Fundamental Workflow

When a new large-scale factory begins mass production, the process typically starts with a site survey, followed by the basic design of the facility layout, construction of the plant, procurement of major equipment, preparation of tools and fixtures, recruitment of workers, and finally trial production before full-scale manufacturing can commence.

As I have emphasized repeatedly, the construction of a pyramid—particularly in the case of Khufu's Pyramid, which required the extraction and placement of 2.3 million stone blocks—should be understood not merely as civil engineering but as a mass-production system. Sustained and smooth operation required a high degree of process organization and workflow management.

This was not the first project of its kind. Through the construction of the Meidum Pyramid, the Bent Pyramid, and the Red Pyramid, substantial know-how had already been accumulated. The personnel responsible for these projects would have gained experience and subsequently applied it to the construction of Khufu's Pyramid.

In other words, Khufu's Pyramid—despite its unprecedented scale—was considered feasible precisely because the builders already possessed the necessary expertise. It was not an improvised undertaking.

In this chapter, I proceed under the assumption—supported by evidence from the Meidum and Bent Pyramids—that core masonry and the placement of unfinished casing stones were carried out in parallel, that scaffolding and ramps were extended upward with each completed

course, and that after the core reached its full height, the casing stones were cut and polished, followed by the removal of scaffolding and ramps.

2. Constraints Imposed by the Geometry of a Square Pyramid

Unlike modern high-rise office buildings, which are typically rectangular prisms, a pyramid is a square pyramid, a distinctive form that imposes important constraints on workflow management.

It is intuitively clear that if the side length is reduced to one-half, the area becomes one-quarter; if reduced to one-quarter, the area becomes one-sixteenth. The same principle applies to the number of stones required per course.

Although actual pyramids use larger stones at the bottom and smaller stones at the top, I simplify the calculation by assuming uniform block size. With a base length of 230 m and 203 courses, the approximate total number of blocks can be estimated using:

Total blocks=$(n/3)\times 203$

where n is the number of blocks in the first course.

Given the known total of 2.3 million blocks, we obtain:

n=33,990 blocks in the first course

≈184 blocks per side

Block width≈1.25 m

Using this model, the number of blocks per course decreases rapidly: 1st course: 33,990, 10th course: 31,043, 20th course: 27,925, 50th course: 19,561, 100th course: 8,921, 150th course: 2,405

These values are approximate, but the key point is that the number of required blocks decreases quadratically as construction progresses upward. In reality, the decrease is less steep because upper stones are smaller, but the overall trend remains valid.

3. Imagining Myself as a Mason Working on the Pyramid

Earlier, I estimated the total length of the ramp at 6.2 km, but because

the pyramid is a square pyramid, the side length decreases with height, and so does the length of the circumferential ramp. For example, at the 80th course, near the stress-relieving chambers above the King's Chamber, the ramp length has already shrunk to about 4 km, and the remaining distance from the 80th to the 203rd course is only 2.2 km.

At this point, I tried to imagine myself as a laborer working on the upper levels of the pyramid. Near the Giza plateau, archaeological remains of workers' barracks have been found. Stonecutters working on the ground and transport workers moving blocks from the quarries to the pyramid may have commuted from these barracks. But what about the workers on the upper levels?

If it were me, I would likely not return to the barracks each day. Instead, I would sleep and live on the broad working platforms of the pyramid itself. Rain is extremely rare in this region, so a simple mat would suffice for sleeping comfortably in summer. Facilities for cooking, food distribution, and latrines were likely set up in corners of these platforms. With work and living spaces adjacent, there would be no commuting time, and rest breaks and shift changes would be extremely efficient.

But then I realized: what happens near the top?

Such spacious platforms cannot exist near the summit. Moreover, the number of core and casing stones decreases drastically, and the working area becomes extremely limited, restricting the number of workers who can operate there. And the summit is 6 km away from the ramp entrance at ground level.

What would the construction site have looked like from afar during this final stage, when only a small number of workers were building the last section of the ramp, placing the final core stones, and installing the final casing stones?

In the early stages, vast numbers of workers transported and laid out the core stones at the base. Even after ramp construction began and the pyramid rose upward, large numbers of workers were still involved. Compared to that, the number of workers near the summit would have been dramatically smaller, making the site appear almost inactive—even

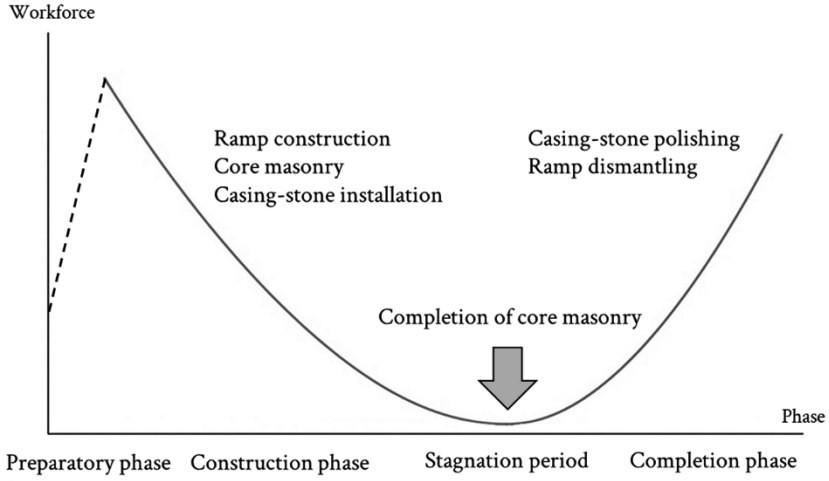


Fig. 6-1. Workforce Dynamics and Construction Phases

though the project was approaching its most critical milestone: the completion of the core and the installation of the final casing stones.

Those few workers near the summit must have worked with great determination. Yet even if supervisors wanted to push progress by adding more workers, there was simply no space to deploy additional personnel. Supervisors would have been powerless in the face of such physical constraints.

Thus, even though the number of stones per course decreases sharply as construction progresses, the time required per course does not decrease proportionally. This is an important point.

When viewed in this light, pyramid construction was not a uniform process. The number of workers required varied dramatically depending on the stage of construction.

4. Changes in Required Workforce Over the Construction Period

Fig. 6-1 illustrates, in schematic form, how the number of workers fluctuated throughout the construction process. As shown in the figure, the construction period of a pyramid can be divided into four major

phases: the preparatory phase, the construction phase, the stagnation phase, and the completion phase. In the first half of the project, the primary tasks were the construction of the ramp, the laying of core masonry, and the placement of casing stones. In the latter half, the main tasks shifted to cutting and polishing the casing stones and dismantling the ramp.

4-1. Preparatory Phase:

In the case of Khufu's Pyramid, this phase included:

initiation of basic design,

site surveys,

bedrock investigations (including test pits and excavation of the subterranean chamber),

quarrying and stockpiling of core stones,

preparation of casing stones,

production and accumulation of sun-dried mudbricks for ramps and scaffolding,

construction of transport routes and ramps for stone and material delivery,

excavation, dredging, and construction of Khufu's harbor,

construction of workers' barracks,

establishment of the project management structure,

and leveling of the bedrock.

It is difficult to estimate the exact labor dynamics of this phase, but once bedrock investigations began, a substantial workforce would have been required. When the feasibility of pyramid construction was confirmed, infrastructure development and the construction of workers' facilities likely began almost simultaneously. Bedrock leveling alone would have required a very large number of workers.

4-2. Construction Phase:

This phase marked the beginning of full-scale construction:

laying of core masonry,

placement of casing stones,

and construction of ramps and scaffolding.

On the design side, detailed planning would have progressed from the entrance passage, ascending passage, and Queen's Chamber to the King's Chamber and its stress-relieving structures, accompanied by verification experiments.

On the construction side, the first course of a square pyramid requires the largest number of stones, and these stones are also the largest in size. Thus, a very large workforce was needed to launch the project with a massive initial effort. However, this did not require mobilizing new workers from scratch; many of the workers already engaged in infrastructure development and bedrock leveling during the preparatory phase could be reassigned.

Here the unique geometry of a square pyramid becomes critical: with each completed course, the working area shrinks, and accordingly, the required number of workers for masonry, quarrying, and transport decreases.

In Fig. 6-1, the decline is shown as a quadratic curve, but if one ignores practical constraints such as maximum workforce capacity, the theoretical decline would resemble a cubic curve, dropping even more sharply. Such a curve is unrealistic, so a quadratic approximation was used.

This observation reveals an important fact:
the farmers conscripted during the agricultural off-season were not kept for twenty years straight.

It is incorrect to imagine "tens of thousands of farmers being conscripted continuously for two decades." Many would have been released from duty after only a few years, and the number of exempted workers would have increased rapidly as construction progressed.

4-3. Stagnation Phase:

As the completion of the core approached, both the quantity of stone and the available working space decreased, forcing a reduction in workforce. Compared to the early stages, only a few dozen workers

would have remained near the summit, and the frequency of stone deliveries would have dropped dramatically. To an outside observer, the project might have appeared to have come to a halt.

By the time the final core stones and casing stones were placed, the workforce had shrunk to a minimal number.

The celebration marking the completion of the long construction process was likely attended only by this small group—the vast majority of workers, supervisors, and designers had already left the site. Few of those who had witnessed the beginning of construction would still have been present.

With the completion of the core, the nature of the work changed dramatically. The main tasks now became finishing and polishing the casing stones and removing the ramp. Initially, the limited working space allowed only a small number of workers, but as work descended to lower courses, the required workforce increased again.

4-4. Completion Phase:

Although finishing the casing stones and dismantling the ramp are part of the final stage, the workforce curve during this phase differs greatly from typical construction projects. As work progresses downward, the surface area of the casing increases, causing the required workforce to rise sharply.

Estimating the labor required is difficult because the time needed to cut and polish high-quality Tura limestone varies greatly depending on the required flatness and surface finish. Polishing, in particular, can dramatically change the total labor hours.

Intuitively, however, the time required for cutting and polishing the casing stones may have exceeded the combined time needed to quarry, shape, and transport a core block. As noted in Chapter 2, tools and production equipment may have been used for quarrying and shaping non-visible surfaces, but finishing the visible casing surfaces had to be done on scaffolding around the pyramid, relying primarily on small tools and manual labor.

One can easily imagine the scene: as the ramp was gradually removed, large numbers of workers and craftsmen crowded around the final courses of casing stones, cutting and polishing them. And once polishing was complete, the workforce would have collapsed from its peak to near zero almost instantly.

Although this topic lies slightly outside the main scope of this book, it is worth noting that managing a construction project with such extreme fluctuations in workforce requirements presents several challenges:

simultaneous ramp-up of many different types of work,

dramatic changes in required skills and occupations between phases,

stagnation-phase management: workforce reductions, reassignment of supervisors, and what might be called "unemployment management" for specialized craftsmen.

5. Seasonal Variations in Work Activities and Workforce Requirements

5-1. Inundation Season (Agricultural Off-Season):

The majority of the labor force responsible for the core tasks of pyramid construction—quarrying, transporting, and setting stone blocks—is now understood not to have been slaves, but rather farmers conscripted during the Nile's inundation, when agricultural work was impossible.

In addition to quarrying and masonry, workers would also have been engaged in:

construction of ramps and scaffolding,

expansion and maintenance of core-stone stockyards,

reinforcement and repair of transport routes,

and other forms of infrastructure development.

These tasks required large numbers of workers and were well suited to the agricultural off-season.

5-2. Low-Water Season (Agricultural Busy Season):

Once the primary labor force—the farmers—returned to their fields,

most construction activities would have slowed dramatically. However, certain tasks were actually best suited to the low-water season.
These included:

collecting Nile mud, the raw material for sun-dried mudbricks,

dredging and maintaining Khufu's harbor,

and especially exploiting the fact that "Khufu's Basin" dried out completely, becoming an ideal site for large-scale mud extraction and brick production.

Other activities likely carried out during this season include:

expansion of quarries,

maintenance and improvement of transport routes,

production and replenishment of consumables such as tools, rollers, and ropes,

and general preparations for the resumption of full construction during the next inundation.

Most of the lower-ranking administrators responsible for supervising pyramid construction probably remained at Giza year-round, even during the agricultural busy season. It is plausible that many of them engaged in mudbrick production, a task requiring little specialized skill.

5-3. Tasks Conducted Throughout the Year:

Certain tasks required skilled, year-round specialists, including:

surveying,

stone cutting,

shaping and polishing,

and toolmaking.

Infrastructure maintenance—such as repairing transport routes, ramps, and scaffolding—was essential for maintaining productivity and therefore likely continued year-round. Technical administrators involved in design and planning would also have remained on site throughout the year.

Bread, the staple food of ancient Egypt, was dense, low in moisture, and resistant to spoilage. Because it stored well, bakeries likely operated at high capacity year-round, building reserves for the next inundation

season when labor demand surged.

Merer's diary suggests that even seemingly simple operations, such as harbor work, were managed by a highly subdivided bureaucratic structure. As described above, pyramid construction involved tasks that varied dramatically by construction phase and by season.

Given the nonlinear and highly variable nature of the worksite, it is reasonable to conclude that the management of pyramid construction was far more sophisticated and meticulous than modern observers might assume.

Part II

The Evolution of the Fourth Dynasty Pyramids

CHAPTER 7

The Three Large Pyramids of King Sneferu

Before entering the main discussion, I would like to outline the reign lengths of the kings of the Fourth Dynasty.
In the Old Kingdom, the reign lengths of individual kings often differ by several decades depending on the scholar, and they are not firmly established.

For example, The Book of Ancient Egypt published by the British Museum lists explicit reign dates only from the Eleventh Dynasty onward, and does not provide reign dates for the Old Kingdom.

In contrast, The Oxford History of Ancient Egypt, edited by Ian Shaw, includes reign lengths for each king, and many publications adopt these figures as their standard.

American publications, however, often rely on Atlas of Ancient Egypt by Professor John Baines and Jaromír Málek, and these figures appear in works by Mark Lehner and Richard Wilkinson.

Table 7-1. Reign Lengths of the Fourth Dynasty Kings

King	British Tradition	Years	American Tradition	Years
Sneferu	2613–2589	24	2575–2551	24
Khufu	2589–2566	23	2551–2528	23
Djedefre	2566–2558	8	2528–2520	8
Khafre	2558–2532	26	2520–2494	26
Menkaure	2532–2503	29	2490–2472	18
Shepseskaf	2503–2498	5	2472–2467	5

Even in the United States, the Metropolitan Museum of Art does not specify reign dates for Old Kingdom kings.

A comparison of the two systems is shown in Table 7-1.

Although the absolute dates differ by 38 years, the reign lengths of Sneferu, Khufu, Djedefre, and Khafre are identical in both traditions.

Only Menkaure shows a discrepancy of eleven years.

In this book, I adopt the British chronology for convenience, but the absolute dating differences themselves are not the subject of discussion.

Other proposals exist, such as Tallet's suggestion that Khufu reigned for 27 years.

Regarding Sneferu, Rainer Stadelmann proposed a reign of 48 years based on numbers written on core stones of the Red Pyramid (Beiträge zur Geschichte des Alten Reiches, MDAIK 43, 1987).

Stadelmann argued that since Sneferu built three large pyramids, his reign must have been longer than 24 years.

However, this book does not adopt such reasoning.

Rather than assuming a longer reign simply because construction seems difficult within 24 years, I examine in Section 4 what methods might have made the construction feasible within the commonly accepted reign length.

1. The Step Pyramid at Meidum

King Sneferu, founder of the Fourth Dynasty, is known for having built numerous pyramids.

He constructed three large pyramids and several smaller ones at sites such as Fayum and Edfu.

The pyramid at Meidum, originally built as a step pyramid, retains sloping remnants at its lower portion.

It was surveyed in the late nineteenth century by Flinders Petrie, who published Medum in 1892.

Petrie recorded the base length as 5,682 inches (approximately 144 m), and noted that the original step pyramid had been converted into a true

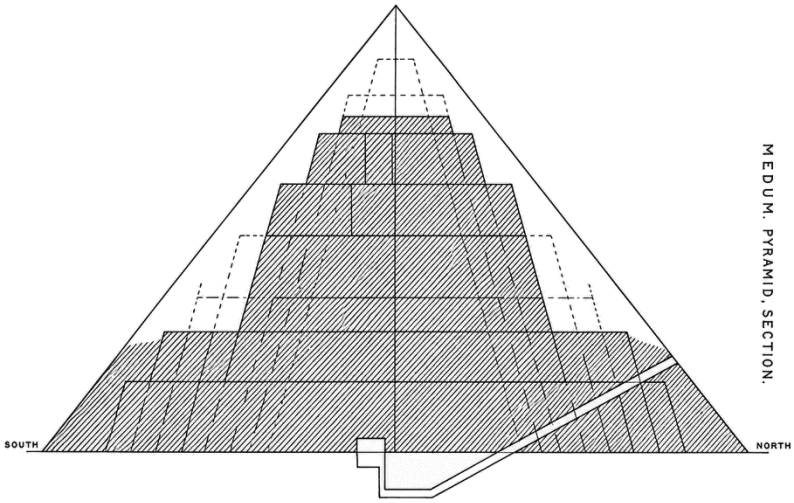


Fig. 7-1. The True Pyramid at Meidum (traced from Petrie's reconstruction drawing)

pyramid by adding limestone casing stones.

His report includes a reconstruction drawing of this form.

Earlier scholarship held that the step pyramid portion was built by King Huni (the last king of the Third Dynasty), and that Sneferu later converted it into a true pyramid.

However, recent studies increasingly support the view that Sneferu built the entire structure from the beginning.

Although the casing stones have collapsed, Petrie's drawings indicate an outer slope of 51.5 degrees.

The text of Medum also states that the slopes of various sections were around 51.5 degrees.

With a base of 144 m, the height would have been approximately 90 m.

Menkaure's pyramid has a base of 104 m and a height of 66 m, with a slope of 51.3 degrees.

Its appearance is similar, but the Meidum pyramid is significantly larger.

Stadelmann argued that the conversion into a true pyramid occurred

in the latter half of Sneferu's reign, after the Bent Pyramid.

However, this overlaps with the construction period of the Red Pyramid, making his claim doubtful.

Following Kurt Mendelssohn's reasoning, it is also possible that the Meidum pyramid began to collapse, prompting a shift to Dahshur.
For these reasons, I consider Meidum to have been the first true pyramid.

Thus, the origin of the large Fourth Dynasty pyramids lies in the step pyramid at Meidum.

When this step pyramid was converted into a true pyramid, it is significant that a construction method fundamentally different from the step-pyramid techniques of the Third Dynasty was devised. As explained in detail in Chapter 5, the scaffolding and ramp system used for true pyramids does not lie on a simple extension of the ramp concepts employed for step pyramids.

2. The Significance of the "Bend" in the Bent Pyramid at Dahshur

The next large pyramid built by King Sneferu is the so-called Bent Pyramid at Dahshur, well known for its distinctive shape.

Since this pyramid was conceived as a true pyramid from the outset, it is reasonable to assume that its construction began around the same time as the conversion of the Meidum pyramid from a step pyramid into a true pyramid.

Meidum and Dahshur are separated by roughly 40 kilometers in a straight line, which in ancient terms would have been perceived as entirely different locations.

Thus, it is not surprising that the two projects may have proceeded independently.

Alternatively, as Kurt Mendelssohn suggested, construction at Dahshur may have begun after the Meidum pyramid started to collapse.

The lower portion of the Bent Pyramid has a slope of 54 degrees, while the upper portion has a gentler slope of 43 degrees.

This change in angle was made during construction.

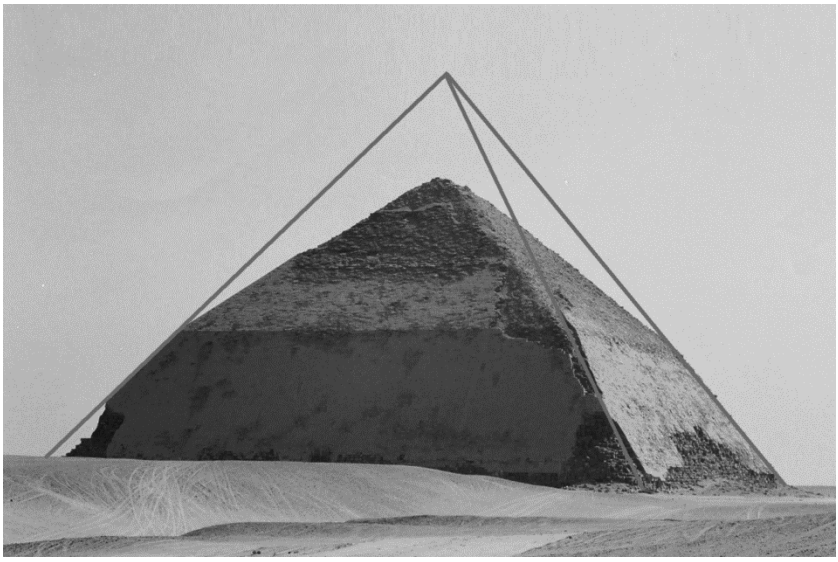


Fig. 7-2. The Bent Pyramid at Dahshur (photograph and virtual reconstruction by the author)

In technical terms, it represents a "specification change," implemented because structural instability—such as deformation and cracking—had begun to appear, indicating an impending collapse.

Although symbolic or religious interpretations have been proposed, such as those by Alexander Varille, traces of structural countermeasures inside the pyramid support the view that the angle was altered to prevent collapse.

This book adopts that interpretation as the working assumption.

Extending the lower ridge line upward reveals the original design intent of the Bent Pyramid.

Its present height is 101 meters, but if the 54-degree slope had been maintained, the height would have reached 130 meters—second only to Khufu's pyramid.

Because a pyramid is a square-based pyramid structure, the load borne by the central portion of the base directly beneath the apex is greatest.

Table 7-2. A Technical Comparison of Horizontal and Inward-Leaning Masonry Techniques in Pyramid Construction

Item	Horizontal Courses	Inward-Leaning Courses
Initial direction of forces	Downward	Downward plus inward toward the center
Condition of the central core	Mostly stable under vertical load	Vertical load combined with concentrated inward forces from surrounding blocks
Behavior when upper loads increase and deformation begins	Deformation spreads gradually outward	Ground pressure rises beyond the original vertical load due to inward horizontal forces
Collapse risk	Detachment of casing stones	Failure of the central structural core

As height increases, this load intensifies, producing deformation pressure.

Thus, the most fundamental countermeasure is to reduce the height by altering the slope.

What deserves particular attention is the decision-making process that led to adopting the gentler slope.

Not only was the angle changed, but the masonry technique was also altered: the lower portion was built using inward-leaning courses (accreted layers), whereas from the bend upward, the builders switched to horizontal courses.

Inward-leaning masonry was a well-established technique known to produce a tightening effect toward the center, thereby strengthening the structure.

However, while effective in preventing the detachment of casing stones, this method increases inward horizontal forces as the pyramid

grows taller.

These forces become enormous, exerting intense pressure on the central core.

With no path for this pressure to dissipate, it translates into increased vertical load, concentrating ground pressure beneath the center of the pyramid and causing subsidence.

Horizontal masonry, by contrast, directs forces primarily downward, reducing excessive load concentration at the center.

Given these technical considerations, the builders reduced the slope from 54 to 43 degrees and adopted the conservative but rational method of horizontal masonry to limit excessive central loading and continue construction safely.

This change strongly suggests that expert technical advice was sought and accepted.

From a project-management perspective, this represents a major shift. A royal construction project—executed according to the will of the king—encountered a structural crisis, and in response, the builders adopted expert recommendations and implemented a bold modification.

The "bend" of the Bent Pyramid thus stands not only as evidence of a structural specification change but also as a sign of a transformation in management style: a willingness to incorporate specialist advice.

3. Technical Continuity and Safety Measures Leading to the Red Pyramid

Although the Bent Pyramid was completed by reducing the upper slope angle, thereby avoiding abandonment or collapse, its unusual appearance was likely unsatisfactory to the king and the ruling elite.

Following its completion, construction of the Red Pyramid began.

The upper slope of the Bent Pyramid is 43 degrees, and the Red Pyramid was built with exactly the same slope.

This indicates that the technical guidelines (specifications) adopted during the "bend" were strictly carried forward into the next project.

Fig. 7-3. The Red Pyramid (photographed in 2008)

Furthermore, the masonry technique used in the Red Pyramid follows the same horizontal-course method employed in the upper portion of the Bent Pyramid.

In fact, it is possible that the Red Pyramid could have been completed with a steeper angle.

However, the project leaders and technical specialists likely adhered to the proven 43-degree design, prioritizing structural safety and design margin.

Thus, the management style established during the construction of the Bent Pyramid—one that incorporated expert advice—was continued.

Another point of change from the Bent Pyramid to the Red Pyramid lies in the shape of the core stones.

Figure 7-4 shows photographs of core stones from a collapsed section of the Bent Pyramid (left) and core stones of the Red Pyramid (right).

Compared with the Bent Pyramid, the stones of the Red Pyramid are noticeably flatter.

Judging from the person standing near the entrance in the photograph, many of the blocks appear to be rectangular stones approximately 1.2

Fig. 7-4. Masonry Blocks of the Bent Pyramid (left) and the Red Pyramid (right) (photographed in 2008)

meters long and 0.7 meters high.

This indicates a substantial change in stone shape.

The horizontal-course masonry of the Red Pyramid is also clearly visible.

The Red Pyramid has a height of about 104 meters, but because of its gentle slope, its base length reaches 220 meters. This is only about 10 meters shorter than Khufu's 230-meter base and longer than Khafre's 215-meter base.

In other words, in terms of base length, the Red Pyramid is the second-largest pyramid in Egypt.

The emphasis on safety in design resulted in the use of an enormous quantity of stone.

Sneferu, founder of the Fourth Dynasty, is known for building many pyramids.

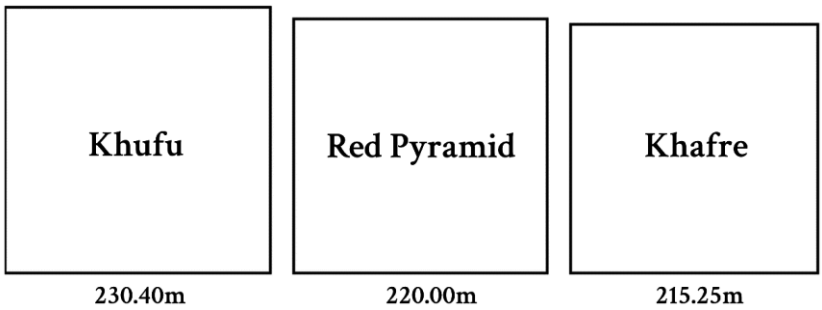


Fig. 7-5. Comparison of Pyramids with Large Base Areas

However, he did not simply construct similar structures repeatedly; rather, each project involved significant technical changes.

The willingness of Sneferu and his administration to accept the "failed" appearance of the Bent Pyramid demonstrates remarkable flexibility.

Their readiness to embrace technical trial and error—"failure as the mother of success"—evokes the adaptive organizational culture of modern startup enterprises.

Nevertheless, although the Red Pyramid was successfully completed, it is likely that the king and his advisors were not entirely satisfied.

4. How Three Large Pyramids Could Be Built During Sneferu's Reign

The reign of King Sneferu is generally considered to have lasted 24 years in both the British and American chronologies, although alternative views exist.

The most notable of these is Rainer Stadelmann's proposal of a 48-year reign, based on numbers found on core stones of the Red Pyramid and interpreted through the biennial cattle-count system.

Stadelmann's reasoning stems from the perception that constructing three large pyramids within 24 years is "mysterious" or implausible.

Figure 7-6 shows the reign lengths of the Fourth Dynasty kings.

The vertical axis represents the reign length, with wider rows indicating longer reigns.

The silhouettes of the pyramids are drawn to the same scale, using the established slope angles.

This comparison makes clear how exceptional Sneferu's 24-year period is: three large pyramids, each comparable in size to those of later kings, were built within a single reign.

The Meidum pyramid is not small; it is larger than the pyramids of Djedefre and Menkaure.

The Bent Pyramid and the Red Pyramid, though not located at Giza, are comparable in scale to the large pyramids there.

Thus, questioning whether three such structures could be built in 24

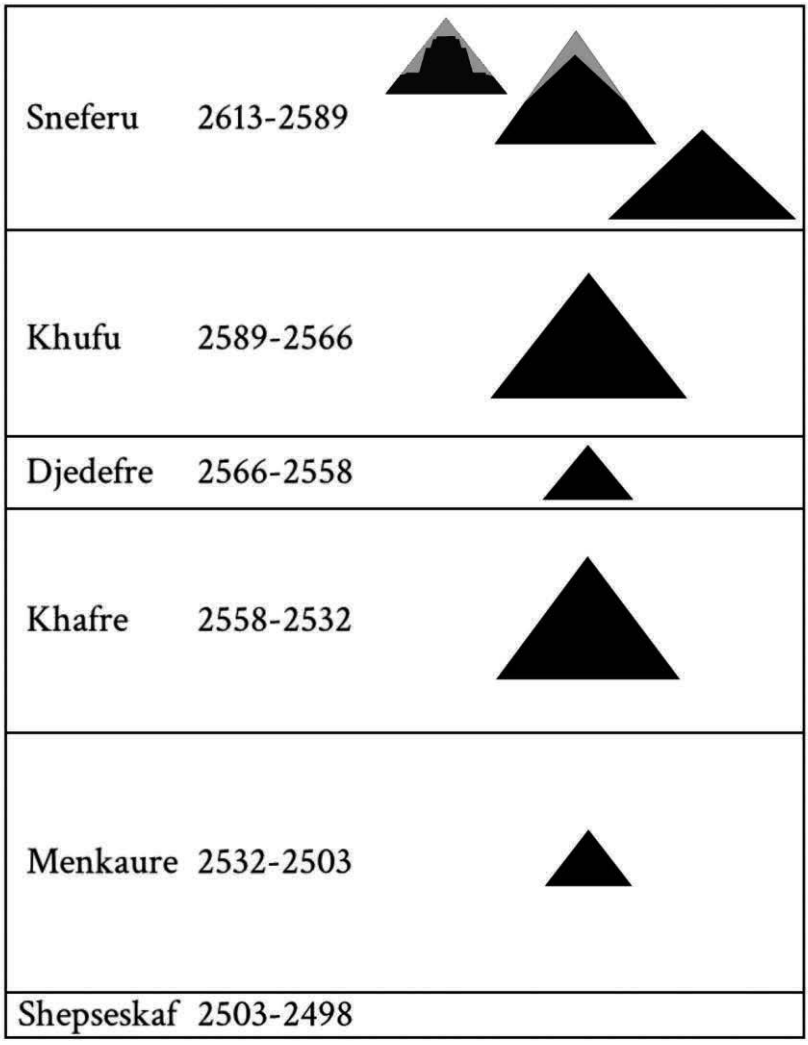


Fig. 7-6. List of Fourth Dynasty Kings and Their Reign Lengths with Associated Pyramids

years is understandable.

Stadelmann begins his argument from this point and presents a table summarizing the total stone volumes of Fourth Dynasty pyramids and associated structures.

Table 7-3. Stadelmann's Average Annual Work Output for Fourth Dynasty Kings

King	Structures	Stone Volume	Reign Length	Average Annual Work Output
Sneferu	Dahshur pyramids and associated temples	3,752,500 m^3	24	156,350 m^3/year
Khufu	Pyramid, subsidiary pyramids, causeway, temples	2,700,000 m^3	23	117,400 m^3/year
Djedefre	Unfinished trench	230,000 m^3	8	28,500 m^3/year
Khafre	Pyramid, valley temple, causeway	2,200,000 m^3	26*	84,500 m^3/year
Menkaure	Pyramid, mortuary temple, subsidiary structures	320,000 m^3	18	18,000 m^3/year

** Khafre's reign length is missing in the Turin King List; Stadelmann supplements it.*

In Table 7-3, the reign lengths follow the Turin King List.

What is striking is that Stadelmann uses Sneferu's exceptionally high average annual work output as the starting point of his argument.

However, as he himself states, "these average annual work outputs naturally contain significant distortions, as the work process was not linear…", acknowledging that pyramid construction varies greatly between the preparatory phase, the main masonry phase, and the finishing phase.

Despite this explicit caveat, he does not sufficiently incorporate it into his subsequent reasoning and again relies on average annual output to discuss reign length.

Stadelmann further asserts that an annual output of approximately 84,500 m^3 would have been feasible, whereas 156,350 m^3 would have

been “absolutely impossible.”

Yet he provides no systematic engineering or organizational justification for this conclusion. He does not demonstrate which processes—quarrying, transport, ramp logistics, staging, placement, casing-stone dressing, or material supply—constituted bottlenecks, nor how these constraints determine the upper limit of annual output.

Thus, his absolute statement cannot be regarded as grounded in engineering analysis.

Moreover, throughout his treatment of the biennial cattle-count system, Stadelmann builds hypotheses upon further hypotheses, and he does not present sufficient evidence to justify interpreting the numbers on foundation stones as regnal years.

Consequently, his proposal of a 48-year reign for Sneferu has not influenced the established chronologies used in either British or American scholarship.

It appears that his argument was ultimately regarded as no more than a speculative hypothesis.

Nevertheless, although Stadelmann’s claims involve certain leaps in logic, the question he raises—whether three large pyramids could be built within 24 years—deserves examination.

Therefore, I deliberately retain the 24-year reign as a fixed premise and consider here whether Sneferu could indeed have completed three large pyramids within that period.

In Chapter 5, I presented Fig. 5-1: Workforce Dynamics and Construction Phases, which proposes that pyramid construction consists of four phases:
the preparatory phase, the construction phase, the stagnation phase, and the finishing phase.

If Sneferu’s three pyramids were built sequentially—Meidum first, then the Bent Pyramid, then the Red Pyramid—each would need to be completed in roughly eight years.

I agree that such a sequential model makes the 24-year timeframe implausible.

However, pyramid construction can be divided broadly into two major phases: the construction phase, involving core masonry and ramp building, and the finishing phase, involving casing-stone polishing and ramp dismantling.

These phases require different types of labor.

Furthermore, the stagnation phase must be considered.

When one pyramid enters stagnation or transitions into its finishing phase, workers involved in quarrying and masonry can be reassigned to another pyramid, enabling parallel construction.

Meidum and Dahshur are separate locations, so it is not unreasonable to assume that construction of the Bent Pyramid began around the time Meidum was being converted into a true pyramid.

In this book, however, I adopt Kurt Mendelssohn's hypothesis that construction shifted to Dahshur because the Meidum pyramid began to collapse.

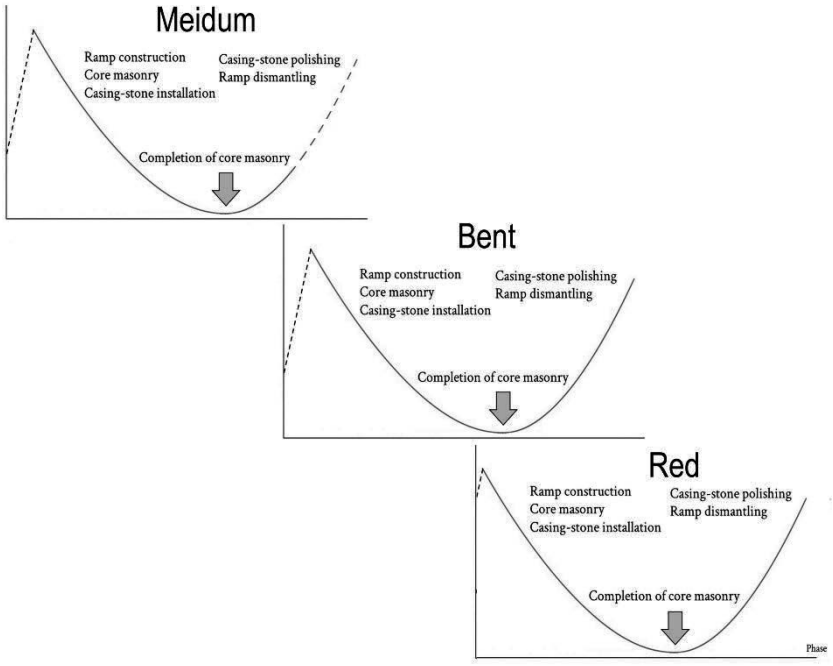


Fig. 7-7. Conceptual Diagram of Pyramids Constructed in Parallel

The reason for building the Red Pyramid after the Bent Pyramid is more straightforward:
although the Bent Pyramid was completed, partial collapse had already begun, making the construction of a new, safely designed pyramid an early necessity.

Under this model, once a pyramid enters its stagnation phase, work on the next pyramid can begin.

The relocation from Meidum to Dahshur required new infrastructure, but the transition from the Bent Pyramid to the Red Pyramid likely benefited from existing facilities, allowing rapid initiation of construction.

Even with parallel construction, building three large pyramids in 24 years is an extraordinary undertaking.

However, I believe it was not impossible.

Why was it feasible to begin new pyramids in rapid succession?

If Meidum began to collapse, and if the Bent Pyramid also showed signs of failure—resulting in its bent shape—then the motivation to build new pyramids was strong.

This is my hypothesis:
before any royal command was issued, quarry workers, laborers, and lower-ranking overseers may have preferred to continue pyramid construction rather than face unemployment or reassignment.

This is a natural human tendency, and even today, large-scale projects often lead to subsequent projects of similar type, driven partly by inertia.

I do not go as far as Mendelssohn, who suggested that pyramid construction had to continue as a national enterprise.

However, pyramid building likely functioned as a kind of flow-production system, making transitions to new projects relatively easy and consistent with the desires of the workforce.

Finally, Stadelmann's paper raises another point of interest: the upper casing stones of the Red Pyramid have not been found.

It is puzzling that the lower casing stones remain while only the upper ones were supposedly removed in later periods.

From the perspective of stone-robbers, removing stones from the lower portion would have been far easier, as seen in the pyramid of Khafre.

It is therefore possible that, to shorten the construction period, the Red Pyramid had its casing stones installed and polished only on the lower portion, and that the upper portion never received casing stones at all.

If so, the finishing phase shown for the Red Pyramid in Figure 7-7 would have been even shorter.

I will discuss this question further in Column 6 at the end of the book.

Column 4. Is "the year after the 13th cattle count of King Khufu" equivalent to his 27th regnal year?

In Japan, both the national fiscal year and the fiscal years of most companies begin on April 1, unlike in Europe and the United States. This makes Japanese readers naturally familiar with the idea that the solar calendar year and the fiscal year do not coincide.

For Western readers, this may seem unfamiliar, but many will recall that in several Western countries the school year begins in September, which likewise does not align with the calendar year.

The 13th cattle count was not conducted on New Year's Day, nor is it even clear in which month it was regularly held.

What is clear is that references to the "nth cattle count" were widely used among officials as a practical means of indicating the year.

Now, what happens if the beginning of the new year and the cattle count event were not synchronized?

If the 13th cattle count had already taken place, the new year had begun, and the 14th cattle count had not yet occurred, then describing that moment as "the year after the 13th cattle count" would be entirely natural. In school terms, it would be like becoming a second-year student in September, then celebrating the New Year while still being a second-year student until the following August.

There is nothing strange about this.

Therefore, the mere presence of the expression "the year after the cattle count" does not logically imply that the cattle count was biennial.

On the contrary, the apparent absence of expressions such as "the second year after the cattle count" suggests that the cattle count—although its timing may not have been fixed—was likely conducted annually.

At the very least, the claim that "the cattle count was normally biennial, but during Khufu's reign it was exceptionally annual" seems to me an arbitrary and strained interpretation.

Thus, “the year after the 13th cattle count of King Khufu” may correspond not to his 27th regnal year, but rather to his 14th year.

More strictly speaking, since we do not know whether the cattle count was annual, the only logically accurate description would be: “the year after the 13th cattle count, at a time when the 14th had not yet taken place.”

In other words, the number of cattle counts cannot serve as a reliable measure for calculating regnal years.

After drafting this column, I became aware of William S. Smith’s 1952 article Inscriptional Evidence for the History of the Fourth Dynasty.

Smith, writing at a time when the biennial-count theory was widely accepted in British Egyptology and when the Turin King List’s figures were treated with great authority, struggled to reconcile these conflicting data.

He even proposed that during Sneferu’s reign the cattle count may have shifted from biennial to annual partway through.

Yet Smith’s scholarly attitude was cautious. He refused to treat inscriptions containing only numbers as valid evidence unless they included full date formulae; he noted that the phrase “the year after” does not necessarily imply a biennial system; and he pointed out contradictions between the Palermo Stone and the biennial-count theory.

Thus, although he leaned toward the biennial interpretation, he did not regard it as absolute.

Gardiner, in "Regnal Years and Civil Calendar in Pharaonic Egypt," identifies the hieroglyphic notation for "occasion" ( ), which combines with "before" or "after" to form cattle-count date formulas. Whether this notation is present or absent is likewise significant.

It is somewhat regrettable that both Smith's careful scholarly stance and the contradictions he identified have largely been forgotten, and that the biennial-count theory is now often treated as if it were firmly established. There remains, in my view, ample room for re-examination.

CHAPTER 8

Khufu's Pyramid: The Return to a Steep Angle

After Khufu ascended the throne, the construction of his pyramid was almost certainly considered immediately.

I believe that within the king's circle and among the ruling elite, the ideal forms envisioned were those his father Sneferu had desired but ultimately failed to realize: a true pyramid with a 51.5-degree slope—achieved by adding casing stones to a step pyramid—and the original 54-degree design of the Bent Pyramid before its change in angle.

Although the Red Pyramid was completed, its gentle, hill-like profile may have felt insufficient to those who sought "a taller and more sharply pointed monument"—a form that embodied what a royal pyramid ought to be.

Fig. 8-1. The Pyramid of Khufu (photographed in August 2008)

A crucial point often overlooked is this: While the Bent Pyramid appears today as a conspicuously "failed" structure due to its mid-construction change in angle, the Step Pyramid at Meidum—despite its outer casing having already begun to deteriorate and collapse even in antiquity—would not have appeared as the bare core we see today. At that time, it likely still retained the external form of a true square pyramid, allowing observers to see directly a pyramid with a 51.5-degree slope.

This ability to see the Meidum Pyramid in its near-original form is, in my view, extremely important.

The overwhelming impact of Khufu's Pyramid is not felt in distant photographs, but when one stands at its base and looks upward. The sense of looming pressure—almost a physical force—is directly tied to the slope angle. There is a profound difference between slopes below 45 degrees and those above 45 degrees, a difference that cannot be captured by the mere numerical gap of eight degrees.

Anyone with skiing experience will understand this intuitively: Once a slope exceeds 45 degrees, skiers often describe it as a "cliff" or a "wall." Even a small numerical difference can produce a dramatic change in human perception.

This sense of pressure—of being overwhelmed—is precisely what makes a pyramid effective as a monument of royal authority. In a sense, it is the very metric by which a pyramid's value is judged.

I have stood at the base of the mausoleum mound of China's First Emperor and at the Pyramid of the Sun in Teotihuacan. Both are undeniably massive, yet neither produced the overwhelming impact I felt beneath Khufu's Pyramid. The difference lies in the slope: both the First Emperor's mound and the Pyramid of the Sun have relatively shallow angles, and thus the impression they create is fundamentally different.

If Khufu and the elites of his time stood beneath both the Meidum Pyramid and the Red Pyramid, they would have experienced—viscerally—the stark difference in pressure and intimidation produced by their respective slopes.

The Meidum Pyramid is thought to have been about 90 meters tall.

The Red Pyramid is taller at 104 meters, yet if the Meidum Pyramid still retained its true-pyramid form in Khufu's time, standing at its base would likely have made it feel taller and more imposing than the Red Pyramid.

Compared in this way with the Meidum Pyramid, or with the lower portion of the Bent Pyramid, the Red Pyramid may well have struck observers as lacking the force expected of a monument to royal authority. This visual and psychological consideration may have been among the factors behind Khufu's decision to return to a steep slope.

However, Khufu's design specifications—52 degrees and a height of 146 meters—were extraordinarily demanding.

A note on terminology is in order here. Egyptological literature conventionally describes the slope of Khufu's Pyramid as "51 degrees," apparently by simply dropping the minutes rather than rounding them. I depart from this convention and use "52 degrees" throughout this book. Petrie's own survey of the casing stones (The Pyramids and Temples of Gizeh, 1883) reports a mean angle of 51°52′ ± 2′—within measurement error of 51°50′. Rounded to the nearest whole degree, this is 52, not 51, and I see no reason to perpetuate that imprecision here.

It is often assumed that the Bent Pyramid, the Red Pyramid, and Khufu's Pyramid represent a straightforward technological progression. I do not believe this. Rather, the path leading to Khufu's Pyramid was a zigzagging line shaped by alternating priorities.

The Bent Pyramid, whose drastic mid-course design change was forced by structural instability, served as a cautionary example. The Red Pyramid, built with a safer construction method and a conservative slope, embodied a design philosophy centered on safety margins. Khufu's Pyramid, by contrast, represented a return to a steep angle and an unprecedented height—a bold specification that broke from the conservative trend.

1. Selecting Giza as the Construction Site—The Limestone Bedrock

Faced with such extremely demanding design specifications, the

pyramid project must have begun examining concrete measures immediately.

The project team's greatest concern would undoubtedly have been the steep slope angle, which directly translated into increased ground pressure at the base of the pyramid.

Since uneven ground conditions were the direct cause of the "bend" in the Bent Pyramid, the selection of a suitable foundation was the most critical issue. By this time, the project members were already aware that the ground at Dahshur was weak. It is therefore highly likely that the engineering side strongly advocated relocating the construction site.

The site ultimately chosen as a candidate was Giza, located roughly 26 km north-northwest of the Red Pyramid. The area is a raised plateau where limestone bedrock is exposed at the surface, making it appear to be an ideal location with strong, stable bedrock.

Moreover, because Giza is a plateau, the pyramid would have been visible from great distances. In ancient Egypt 4,500 years ago—when the surrounding landscape was far less obstructed than today—the pyramid would have been visible from an even wider area.

According to the study by Hader Sheisha and colleagues, a branch of the Nile—what modern scholars call the "Khufu Branch"—once flowed close to Giza. This would have made it possible to transport materials by water.

Most decisive of all, however, was that the primary construction material—limestone—could be quarried directly at the site.

The Red Pyramid is estimated to have required roughly two million limestone blocks. By that stage, the project team must have fully recognized that transporting such a vast quantity of stone was a major logistical challenge.

Khufu's Pyramid required 2.3 million blocks. Although its height is 1.4 times that of the Red Pyramid, the total number of blocks increases by only a factor of 1.15 due to the geometry of a square pyramid. Even so, a 15% increase is a significant burden.

The greatest advantage of Giza was that the main construction material—limestone blocks—could be sourced locally. In fact, there is

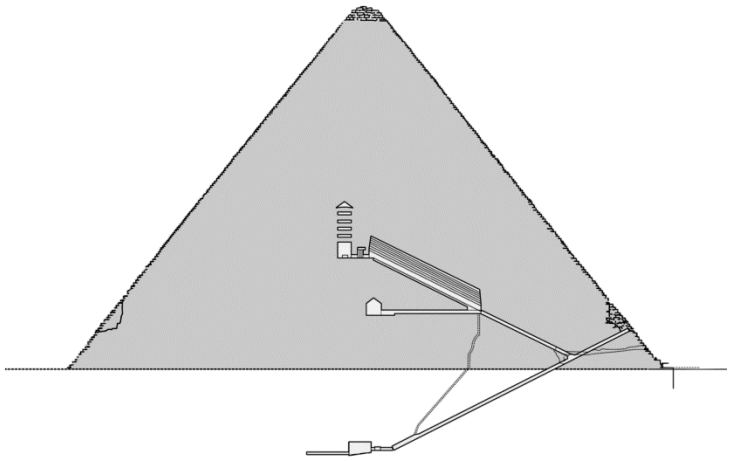


Fig. 8-2. Internal Structure of the Pyramid of Khufu (traced from Howard Vyse, Operations Carried on at the Pyramids of Gizeh)

evidence that Giza had already been used as a quarrying site during Sneferu's reign.

The quarry sites used during Khufu's reign still survive today in areas such as the so-called Central Field, located immediately south of Khufu's Pyramid—so close that it can practically be considered adjacent.

For a project involving such an enormous volume of stone, the advantage of having extremely short transport distances was decisive.

Another important factor was that high-quality limestone for the casing stones came from Tura, across the Nile. Transporting these stones required crossing the river and using water transport.

Dahshur lies upstream from Tura. Therefore, transporting casing stones from Tura to Dahshur by boat would have required sailing against the Nile's current. It is possible that, instead of rowing upstream, the stones were ferried across the river and then transported overland to Dahshur.

In any case, during the construction of the large pyramids at Dahshur, this must have been recognized as a major logistical challenge.

From this perspective, choosing Giza—located downstream from Tura—as the site for an even larger pyramid was a rational and strategically sound decision.

2. Bedrock Investigation and the "Mysterious Subterranean Chamber"

In Operations Carried on at the Pyramids of Gizeh (1837), the joint work of British explorer Howard Vyse and engineer John Shae Perring, a cross-sectional diagram of Khufu's Pyramid depicts not only the structures now known as the King's Chamber, the Queen's Chamber, and the Grand Gallery, but also a deep underground chamber referred to as the "Subterranean Chamber."

In The Great Pyramid Passages and Chambers (1910), John and Morton Edgar published numerous drawings and photographs of the Subterranean Chamber. The walls remain roughly hewn, the floor is unpaved, and the chamber itself is about the size of a 25-meter swimming pool. In one corner, there is a vertical shaft resembling a well.

Even from the photographs included in their book, it is clear that the rear portion of the chamber is in an unfinished state. For a long time, this led to speculation that the chamber represented an "unfinished burial chamber" or that construction of a room intended for religious rituals had been abandoned. However, none of these interpretations gained broad acceptance, and the chamber remained an unresolved "mystery."

What makes this unfinished chamber particularly strange is that while the rear portion remains incompletely excavated, the entrance area shows signs of finished wall-cutting. It is highly unnatural for workers to cut the entrance walls while excavation at the far end was still underway, as this would cause severe interference in the workflow. The preserved state therefore suggests that excavation at the rear was halted first, and only the entrance-side wall-cutting continued afterward. This, however, makes the chamber's purpose even more difficult to understand.

According to Operations Carried on at the Pyramids of Gizeh in 1837, the Subterranean Chamber appears to lie almost directly beneath the central axis of the pyramid.

A descending passage, running from true north toward true south at an angle of 26 degrees and a width of roughly 1.6–2 meters, extends for more than 100 meters. At a depth of about 30 meters below ground level,

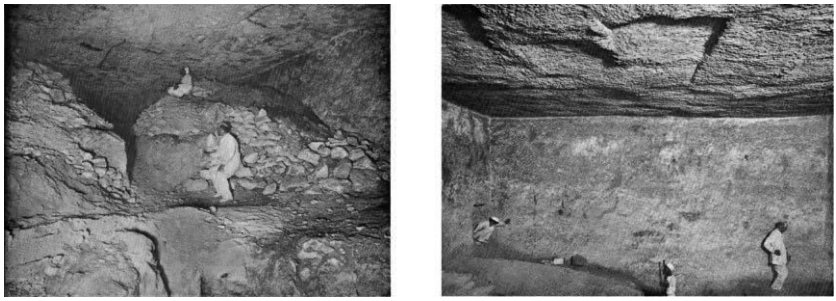


Fig. 8-3. Rear (left) and front (right) views of the Subterranean Chamber (from The Great Pyramid Passages and Chambers, John & Morton Edgar, 1910, public domain)

the passage becomes horizontal, and the chamber lies beyond this point. The surface of this passage (beneath the masonry) lies inside the pyramid's base perimeter. Since it is structurally implausible that the builders carved a passage downward through already-laid masonry, the excavation of this passage must have begun before the first course of stones was set, and the passage was extended downward as construction progressed.

The slope of this passage—26 degrees—is shared by the descending passages of many pyramids, corresponding to a gradient of 50%. This strongly suggests that the passage was excavated from the outset with the explicit intention of reaching a chamber 30 meters below ground.

Even though Giza had been selected as the construction site, the project members—drawing on their experience with the Bent Pyramid—must have been deeply concerned about whether the bedrock could withstand the enormous ground pressure of such a massive pyramid. It is reasonable to assume that they conducted what we would today call a geotechnical boring survey. Exposed bedrock outcrops are weathered and cannot be evaluated solely from the surface. The thickness of the bedrock cannot be known from surface inspection alone, nor can one determine whether the rock is uniform or contains micro-fractures, voids, or other features that could compromise stability. A thorough bedrock

investigation would have been indispensable.

This is common sense even today: large structures require geotechnical surveys, and in earthquake-prone Japan, even ordinary residential houses cannot be built without one.

At this point, I asked myself:

If I were a member of the pyramid project, where would I want to investigate the ground most thoroughly?

Naturally, the most critical point would be the location of maximum ground pressure—the point directly beneath the pyramid's apex, the exact center of the structure.

Then it struck me:

There is a "mysterious subterranean chamber" located 30 meters below the center of the pyramid.

Although I still consider the possibility that the chamber may originally have been intended as a burial chamber, I began to suspect that it might also be related to bedrock investigation.

However, for a chamber to serve as a geotechnical test site, it would need to be located precisely beneath the center. If it were 10 meters off, one could confidently say it was not intended to examine the central ground conditions. Even a deviation of 5 meters would only allow a weak argument that it "might" have been intended for that purpose.

In recent years, laser-based measurement technologies have greatly improved the precision with which the internal structures of Khufu's Pyramid can be mapped.

These measurements have revealed the exact positional relationship between the Subterranean Chamber and the pyramid's center point, as shown in Fig. 8-4.

The north–south centerline of the pyramid passes almost directly through the middle of the Subterranean Chamber. The northern wall of the chamber—the wall on the passage-entrance side—is parallel to the east–west centerline and lies 1.94 meters south of it.

In other words, a person standing on the pyramid's north–south axis can look straight ahead and observe the bedrock located 30 meters below

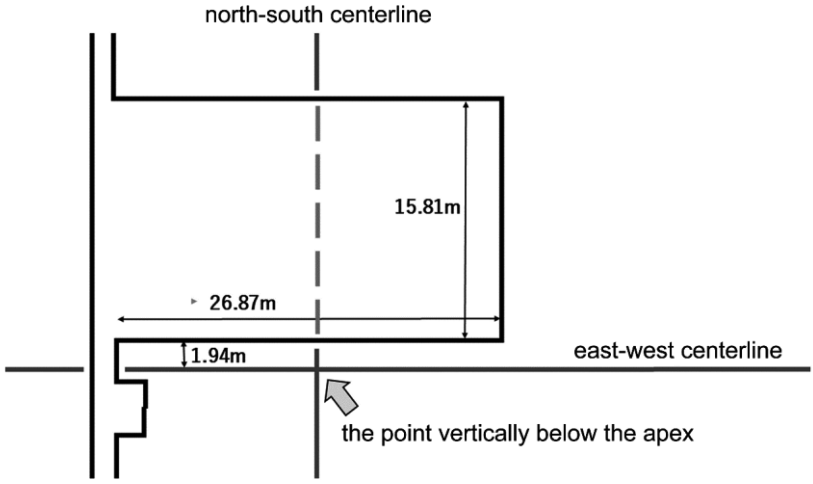


Fig. 8-4. Positional relationship between the Subterranean Chamber and the north–south and east–west centerlines (created with reference to khufupyramid.dk)

the east–west axis, as if viewing a large screen directly in front of them.

This led me to consider that the chamber was not merely a test pit excavated to examine the bedrock down to a depth of 30 meters, but also a monitoring post used throughout the entire construction period to observe whether the steadily increasing ground pressure—caused by the accumulation of millions of stone blocks—was producing any harmful effects on the underlying rock.

The features they would have monitored likely included:
cracks forming on the chamber walls
small steps or displacements in the rock layers
falling grains of sand from the ceiling
unusual sounds caused by damage within the bedrock

Although the northern wall is actually offset 1.94 meters from the east–west axis, this deviation is understandable. In ancient Egypt, two points separated by more than 100 meters along a narrow descending passage could not be observed directly; they had to rely on rope-based surveying. Moreover, the passage descends at 26 degrees, making precise

measurement extremely difficult.

Even in Operations Carried on at the Pyramids of Gizeh in 1837, the diagram shows a slightly different positional relationship, with the center point falling inside the chamber. This means that even 19th-century measurements carried errors exceeding two meters.

The personnel responsible for continuous monitoring were likely lower-ranking administrators. Since the chamber functioned as a worksite, there was no need to pave the floor or finish the walls and ceiling. In fact, leaving the ceiling roughly hewn would have made it easier to detect falling particles or other signs of instability.

In one corner of the chamber is a vertical shaft resembling a well, but its purpose remains unexplained. Given its location, it clearly was not intended for drawing water.

Because the chamber is carved into limestone bedrock, groundwater would have been a serious threat. Water can weaken limestone, dissolve it to form cavities like those in karst terrain, or seep through micro-fractures—any of which would indicate instability. The mere presence of groundwater seepage would imply the existence of continuous fine cracks.

When all of this information is considered together—the chamber's precise location beneath the pyramid's center, the presence of the unexplained vertical shaft, and the unfinished yet functional nature of the space—it becomes increasingly plausible that this chamber served as a monitoring post. Its purpose may have been to detect abnormalities in the bedrock directly beneath the pyramid's center and to ensure that groundwater did not infiltrate the area during construction.

However, this hypothesis would collapse unless the depth of the vertical shaft matched the maximum historical water level of the Nile. Although various surveys of the Giza Plateau exist, many lack clearly defined elevation reference points, and for a long time I was unable to confirm the necessary data.

This changed when I examined the study by Dr. Gamal Younes and colleagues, The pyramid builders' waterways: Reconstructing the ancient

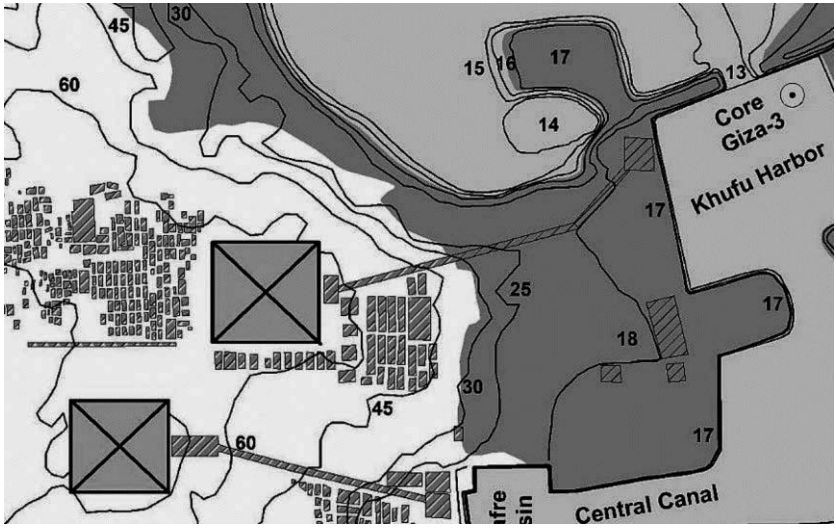


Fig. 8-5. Contour map of the area surrounding the Pyramid of Khufu, showing zones where Nile alluvial mud remains (shaded areas)

topography of Khufu's Pharaonic Harbour at Giza, Egypt. Their maps show that the Pyramid of Khufu stands at an elevation of 60 meters plus α, and that the alluvial mud deposited by ancient Nile floods reaches the 30-meter contour line.

Since the Subterranean Chamber lies 30 meters below the pyramid's base, excavating the vertical shaft an additional depth of α from the chamber floor would have reached the maximum flood level of the ancient Nile. In other words, by digging this shaft, the builders could confirm whether the bedrock beneath the pyramid had ever been eroded or weakened by past extreme floods.

Furthermore, the fact that the chamber itself is located at a depth of 30 meters means that it was deliberately positioned above the highest historical water level. This suggests that the chamber was intentionally placed as deep as possible within the bedrock while still remaining above the maximum flood elevation—a depth chosen with clear purpose.

As construction progressed and millions of stone blocks accumulated, the ground pressure at the pyramid's center would have increased

steadily. If any harmful effects on the bedrock had been detected, it would have served as a warning that a crisis similar to the near-collapse of the Bent Pyramid was unfolding. For the project members, continuous monitoring would have been essential.

One might question whether ancient Egyptians possessed a "monitoring mindset" comparable to modern engineering practice. Yet the existence of Nileometers, systematic astronomical observations, and other long-term measurement traditions suggests that continuous monitoring was entirely natural within ancient Egyptian culture.

The pyramid project members were deeply concerned about vertical ground pressure. Today, with modern structural mechanics and material science, we know that the ground pressure beneath Khufu's Pyramid is approximately 120 tons per square meter, and analyses show that the limestone bedrock at Giza has more than sufficient bearing capacity to support this load (Hemeda, S., and A. Sonbol. 2020. "Sustainability Problems of the Giza Pyramids." Heritage Science 8: 8.).

Therefore, the monitoring post 30 meters underground likely detected no abnormalities throughout the construction period.

However, the Egyptians of 4,500 years ago had no way of knowing this safety margin. Their anxiety about ground pressure must have been constant.

3. The Struggle with Gravity Load Distribution

One of the most distinctive features of the Pyramid of Khufu is the complexity of its internal structure. This includes not only the Grand Gallery and the elaborate gravity-relieving systems above the King's Chamber, but also the unused Queen's Chamber and the numerous voids that have been discovered in recent years.

From the perspective of technical project management, the internal spaces of Khufu's Pyramid can be broadly divided into two categories.

The first category consists of the Queen's Chamber, the Grand Gallery, the King's Chamber, and the gravity-relieving structures—spaces that

were ultimately not used for their presumed original purposes. These appear to represent a heavily reinforced safety-oriented design philosophy, in which every conceivable idea was incorporated during the planning stage (see Fig. 8-2).

Technically, the pyramid employs three major structural methods:

1. corbelled construction
2. gabled roofs
3. flat ceilings formed by massive stone beams

Among these, corbelled construction involves stacking stones so that each successive layer projects slightly inward, creating the necessary space for passages or chambers and resulting in a high ceiling. This technique was used in the burial chambers of Sneferu's Bent Pyramid and Red Pyramid, and in Khufu's Pyramid it appears most prominently in the ceiling of the Grand Gallery.

The Grand Gallery itself is a structure whose design intent is difficult to understand. In the Dahshur pyramids, corbelled vaulting clearly served to protect the burial chamber. But the Grand Gallery is merely a passageway. It is unclear why such an enormous gravity-relieving structure was required for a space that is not a chamber.

From its spatial relationship with the Queen's Chamber and the horizontal passage leading to it, I suspect that the Grand Gallery's

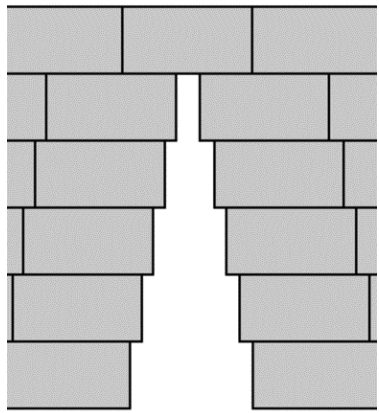


Fig. 8-6. Conceptual diagram of the corbelled construction

Fig. 8-7. The massive gabled structure above the original entrance of the Pyramid of Khufu (photographed in 2008; the lower area with tourists marks the looters' tunnel now used as the modern tourist entrance)

gravity-relieving design may originally have been intended to protect the Queen's Chamber and its approach. In other words, the Grand Gallery may have begun as a structural solution for a chamber that ultimately went unused.

The next major structural method is the gabled ceiling. In Old Kingdom Egypt, the true arch—developed in Mesopotamia and later widely used in Roman triumphal arches—was not yet known. Thus, the gabled ceiling was the established method for resisting vertical gravitational loads. I believe that Khufu's Pyramid represents the earliest known use of this technique in a pyramid. Gabled ceilings appear above the Queen's Chamber, at the uppermost tier of the gravity-relieving system above the King's Chamber, and above the original entrance.

The massive gabled stones above the entrance are particularly striking. In Fig. 8-7, the presence of tourists provides a scale reference, making the enormous thickness of the stones immediately apparent—and they are

laid in two layers. When one stands before this structure, it conveys not a sense of rational minimalism but rather an unmistakable intention to pursue the maximum possible safety, regardless of cost. To me, the gabled stones themselves feel like a silent declaration:

"Beyond this point lies a space that cannot be governed by rationality alone."

Another technique is the flat ceiling supported by thick stone slabs or beams, a method commonly used for passage ceilings. In Khufu's Pyramid, the ceiling of the King's Chamber is formed by massive granite beams, and above them an additional gravity-relieving system was constructed.

It seems unlikely that the builders rigorously evaluated whether such complex structures were strictly necessary. Rather, they appear to have taken every possible precaution in advance to counter vertical gravitational loads. This attitude resembles the approach taken in the Red Pyramid, where safety was prioritized over economic efficiency, resulting in the conservative 43-degree slope.

In Khufu's Pyramid, the burial chamber appears to have shifted progressively upward during the design process—from the initial subterranean chamber, to the unused Queen's Chamber, and finally to the King's Chamber.

A second group of internal features consists of the numerous voids whose shapes and locations lack consistency. These were not part of the original design; rather, they appear to be ad-hoc responses to problems encountered during construction. Their irregular forms, lack of pattern, and unclear purposes suggest that the builders were forced to create additional spaces as they adapted to unforeseen structural issues. These voids seem to be evidence that the struggle against gravity load—and the unintended side effects of that struggle—exceeded the assumptions made during the design stage.

Several well-known structural problems occurred during the construction of Khufu's Pyramid, including the cracking of the granite beams in the King's Chamber and the jamming of the granite blocking system in the ascending passage.

The cracking of the King's Chamber beams refers to the fractures visible in the granite ceiling beams. The French architect Gilles Dormion proposed that the gravity-relieving chambers were hastily added in response to these cracks. However, because the relieving chambers lie directly above the King's Chamber, his theory would require the beams to have cracked before any weight was placed above them—an implausible scenario. Consequently, his hypothesis has not gained support among specialists. The gravity-relieving system was almost certainly part of the original design, intended to distribute the vertical load of the overlying masonry.

The "jamming of the ascending passage" refers to the granite blocking mechanism installed within the Grand Gallery, which became stuck during operation and had to be compensated for with packing stones.

I believe that the jamming of the granite blocking system in the ascending passage was a typical side effect of the project members' extreme fear of vertical loads. Because of this fear, they installed a large gravity-relieving structure above the Grand Gallery. A gravity-relieving structure, by definition, redirects vertical pressure into horizontal pressure. This horizontal pressure can deform the joints between structural elements. I consider the malfunction of the blocking system to be a consequence of this effect.

Given the enormous scale of the gravity-relieving structure above the Grand Gallery, it is likely that the resulting horizontal stresses produced distortions over a wide area. Recent muon-radiography studies have revealed a large void above the Grand Gallery. I do not believe this void was created by the horizontal stresses; rather, it seems to have been an emergency space intentionally created to prevent further propagation of strain.

In other words, the excessive use of gravity-relieving structures—driven by the designers' fear of vertical loads—may have generated horizontal stresses that adversely affected the pyramid's outer regions, particularly the casing stones.

As discussed in Chapter 7, the lower portion of the Bent Pyramid

employed inward-tilted masonry, which produced enormous vertical pressure at the center. This, in turn, imposed excessive load on the weak ground beneath, nearly causing structural failure. In response, the upper portion of the Bent Pyramid adopted horizontal masonry, a method that was then carried over into the Red Pyramid. Khufu's Pyramid also employs horizontal masonry as its basic structural principle.

However, even horizontal masonry produces horizontal stress when subjected to massive vertical loads. This may seem counterintuitive, but stone is not a perfectly rigid body; under pressure, it undergoes slight deformation.

When a vertical load is applied, the stone compresses slightly in the vertical direction and expands laterally. This is analogous—on an extremely small scale—to how bread dough flattens and spreads outward when pressed from above. Although stone deforms far less than dough, the principle is the same: vertical compression produces horizontal expansion, and thus horizontal stress.

The same applies to gabled ceilings, which also generate horizontal thrust.

In a pyramid, the interior is densely packed with masonry, so the horizontal stress is transmitted outward. This outward pressure contributes to cracking and detachment of the casing stones.

It is characteristic of Khufu's Pyramid that multiple, fundamentally

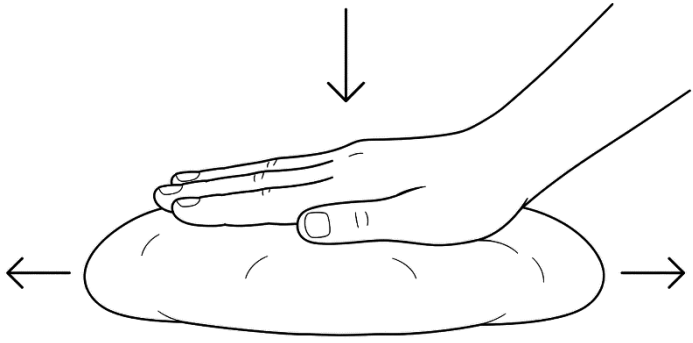


Fig. 8-8. Bread dough spreads sideways when compressed from above

different methods of resisting gravitational loads—corbelled vaulting, gabled ceilings, and massive stone-beam flat roofs—were used simultaneously.

This suggests that the pyramid was not the work of a single brilliant designer, but rather the product of a team of engineers, each with deep expertise in different structural techniques, working together to solve unprecedented challenges.

CHAPTER 9

A Major Delay in Construction

1. How many years did the construction of Khufu's pyramid actually take?

In my view, no definitive evidence establishes the length of time required to complete Khufu's pyramid.

Pierre Tallet, drawing on the Diary of Merer discovered by his team in 2013, argues for Year 27 of Khufu's reign by applying the biennial cattle-count hypothesis.

However, the biennial hypothesis itself is not an established academic consensus.

For example, Zahi Hawass rejects the biennial system and instead proposes Year 17, based on numbers found in the relieving chambers above the King's Chamber.

Yet Hawass's argument is also problematic. According to Howard Vyse's records, other blocks bearing different numbers were found in the relieving chambers, making it untenable to assert that these numbers represent regnal years. Moreover, Hawass's article includes a photograph of a hieratic inscription showing a date, but this is actually a citation from Lepsius's Denkmäler aus Aegypten und Aethiopien, and the readable date comes from Dahshur, not Giza. In the end, Hawass does not present an inscription that explicitly states "Year 17 of Khufu." Thus, his Year 17 proposal lacks the evidentiary foundation necessary to be considered decisive—although it is noteworthy that Hawass does not adopt Tallet's biennial hypothesis.

The only relatively reliable datum is Year 14, derived from reading

Merer's diary without applying the biennial hypothesis. Even then, Merer's involvement in transporting casing stones from Tura is Tallet's interpretation; the diary itself does not explicitly state this. Therefore, even the assertion that "casing stones were being transported in Year 14" should be treated with caution.

Since the two proposals hinge on opposite assumptions about the biennial hypothesis, they cannot both be correct—an inherent contradiction.

However, both interpretations contain serious implications for the construction timeline. Tallet's proposal implies that even in Year 27, casing stones were still being transported and the masonry work was ongoing. Hawass's proposal, on the other hand, suggests that the relieving chambers—located at less than half the pyramid's final height—were completed only by Year 17, making it difficult to imagine that the entire pyramid could have been finished within a 20-year period.

It is unclear whether Hawass or Tallet recognize that their interpretations naturally raise the question: Was Khufu's pyramid truly completed before the king's death? Yet neither interpretation appears to be dismissed as "out of the question" within Egyptology, which I find intriguing. Herodotus, in Histories Book II, states that the paved causeway took ten years and the pyramid itself twenty years to build. Egyptologists may privately suspect that even twenty years would have been insufficient.

The average lifespan in ancient Egypt was low due to high infant and child mortality, and even adults often died in their forties or fifties. Adult life expectancy may have been around twenty to thirty years. Within such constraints, the construction of a royal pyramid—required to be completed before the king's death—must have been planned with a realistic timeframe. I consider a target of roughly ten years, with delays extending into the low teens being acceptable. If project members had initially proposed "twenty-five years," the king would likely not have approved the undertaking.

Given the experience gained from building the Bent Pyramid and the

Red Pyramid, setting a target of ten to fifteen years seems reasonable. Conversely, if the target was around ten years, both Tallet's and Hawass's interpretations imply that the actual construction period exceeded the target by more than double.

In any project, the construction period is one of the most fundamental specifications. The schedule is built around it, and the required workforce is estimated accordingly. For pyramid construction, this included quarrying, transport, hauling, masonry, supervisors, food procurement, provisioning, and medical care. Although ancient Egypt did not operate under a monetary economy, the construction period would still have been a basic management parameter. A delay of more than double the target period would hardly constitute a successful project; completion alone would not be the sole criterion of evaluation.

As for the causes of delay, the most obvious is the fear of vertical load (ground pressure), which led to numerous countermeasures. These included the construction of the unused subterranean chamber and the Queen's Chamber. The many mysterious voids detected today likely reflect on-site troubleshooting, rework, and trial-and-error, all of which would have contributed to delays. In short, the combination of heavy, conservative safety design and insufficiently completed architectural planning likely resulted in a major extension of the construction period.

2. Was Khufu's pyramid truly completed?

The complete absence of burial traces in the King's Chamber raises the question of whether Khufu's pyramid was actually completed before the king's death.

It is uncertain whether this question has simply never been seriously considered, or whether scholars have noticed it but refrained from stating it publicly.

No evidence of completion—such as the stela found at the Bent Pyramid's eastern chapel—has been discovered for Khufu's pyramid. Among the monuments associated with Khufu at Giza, the only structure

with clear evidence of completion and sealing is the solar boat, which bears the name of Djedefre. The fact that this single piece of evidence is repeatedly cited in various publications underscores how scarce the relevant data are.

Sneferu is said to have built three large pyramids within twenty-four years. From that perspective, setting a target construction period of ten to fifteen years for Khufu's pyramid would not have been unreasonable. Yet in practice, the construction conditions differed greatly. First, the efficiencies gained from continuous production during Sneferu's reign could not be replicated at Giza. New infrastructure—such as access routes and Khufu's harbor—would have been required. Geological surveys would also have been necessary before selecting the site.

Second, the production system that had been operating continuously from the Bent Pyramid to the Red Pyramid would have wound down after the completion of the latter. Restarting quarrying operations at a new location would have required preparation time. The production and stockpiling of mudbricks would also have been essential. Although Herodotus's claim of ten years for road construction seems excessive, it is plausible that three years passed before masonry work began.

A distinctive feature of Khufu's core masonry is that many blocks appear to have been trimmed on the front face but not fully dressed on all six sides. As discussed in Chapter 2, quarrying by fracture—using powerful impact forces—could have maintained production throughput, but trimming would have required substantial labor. Since horizontal layering became standard after the Red Pyramid, the upper and lower faces of blocks were typically dressed, but dressing all six faces would triple the labor. This pursuit of precision seems to reflect Khufu's emphasis on safety, but it must have significantly affected the construction period.

My suspicion that the pyramid was left unfinished arises from the condition of its summit. I am aware of theories suggesting collapse or the removal of a massive pyramidion in later periods, but photographs raise doubts: if collapse had occurred, would the four sides of the topmost

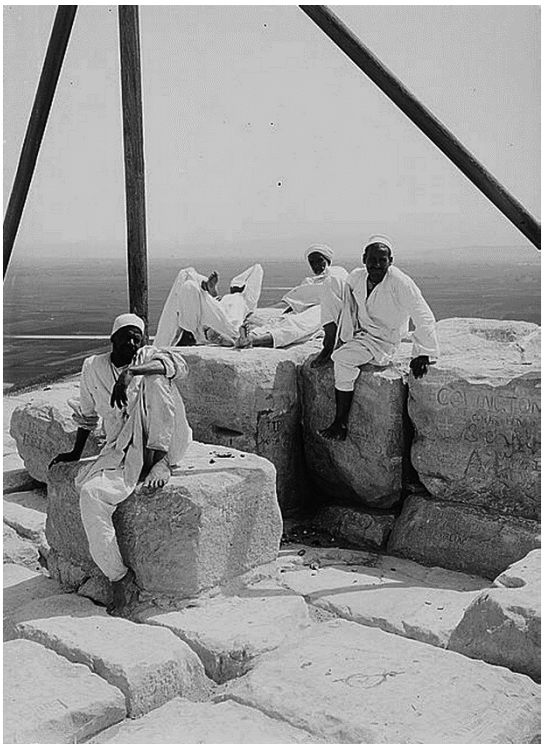


Fig. 9-1. Egyptian views; The pyramids of Gizeh. Summit of the Great Pyramid. (G. Eric and Edith Matson Photograph Collection. American Colony (Jerusalem) Photo Department, ca. 1900–1920.)

completed course really remain as neatly preserved as they are today?

Above the highest finished course, there are partially assembled sections and abandoned blocks.

For more than a century—until its removal sometime between 2019 and 2021—a metal survey tower stood atop the pyramid. The U.S. Library of Congress holds photographs from around 1900–1920 showing the tower's supports. I once suspected that the flatness of the summit resulted from clearing debris during the tower's construction. However, 19th-century illustrations predating the tower show a condition similar to that in Fig. 9-1, suggesting that the current appearance is original rather than the result of modern alteration.

Particularly noteworthy is the state of the masonry where people are seated in Fig. 9-1. If the summit were perfectly flat, the hypothesis of a massive pyramidion might merit consideration. But in the present condition, the course on which people sit (the 204th course) would have had to be completed before any pyramidion could be installed.

The collapse hypothesis is also highly implausible. The stones on which people are sitting or reclining in the photographs are located on the outer edge of the summit. It is extremely difficult to imagine a scenario in which only the stones on the near side would have disappeared as a result of collapse, while the outer stones remained intact.

Furthermore, even if later stone-seekers had removed blocks from the pyramid, there would have been far easier sources of stone near ground level. From a practical standpoint, it would be extraordinarily irrational for them to remove only the core blocks from the summit—the most difficult location from which to extract and transport material.

Thus, rather than interpreting the present condition of the pyramid's summit as the result of natural collapse or deliberate destruction, it seems far less contrived to regard it as the state in which construction was halted for some reason and subsequently left untouched.

If the masonry itself had not yet been completed, then the hypothesis of an unfinished pyramid would be entirely reasonable. Even if the masonry had been completed, however, whether that stage alone constituted "completion" remains open to debate.

For example, the pyramid of Menkaure is clearly complete in terms of masonry, yet it is regarded as unfinished because the outer faces of the lowest granite casing blocks remain unpolished. This demonstrates that, within the field of archaeology, "completion" is not necessarily defined by the mere finishing of the stonework.

Fig. 9-2 illustrates the basic stages of pyramid construction. In the strict sense, true completion should correspond to Stage F, when the polishing of the casing stones and the removal of the ramps have both been finished.

In modern building projects as well, "completion" does not refer to the moment when the exterior structure is finished. A building is considered

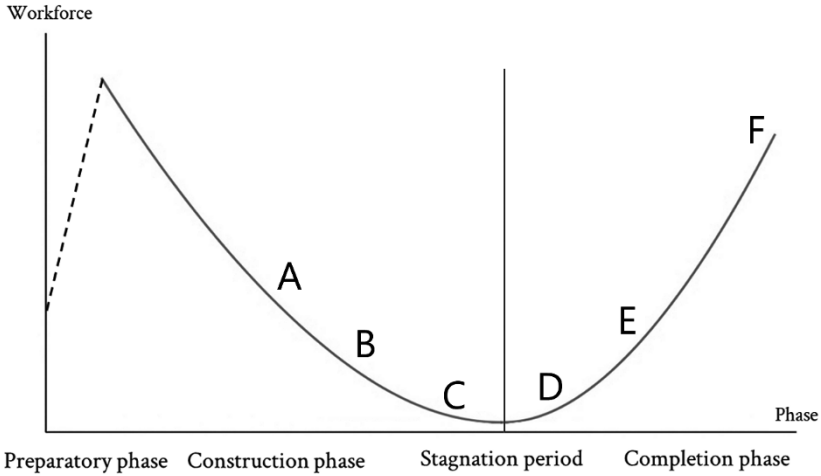


Fig. 9-2. The construction process of the pyramid and considerations regarding the timing of King Khufu's death.

complete only when interior work and auxiliary installations—such as electrical and water systems—are finished and the structure is formally handed over to the client. Although large commercial facilities sometimes open certain sections before overall completion, such "pre-openings" occur only after the client has approved partial handover; the construction company cannot unilaterally declare completion.

In Fig. 9-2, the vertical line between Stages C and D indicates the completion of masonry. However, even if the stonework had been finished at that point, the pyramid would still have been entirely covered by mudbrick scaffolding and the encircling spiral ramp. In this state, the pyramid would have appeared as a massive mound of mudbrick rather than a finished monument.

Once completed, the pyramid and its associated mortuary temple would have functioned as sacred facilities. Thus, the effective "handover" would have been to the priesthood, likely through a religious ceremony. From this perspective, it is doubtful that the pyramid in Stages D or E—still encased in mudbrick—could have been regarded as a completed sacred monument ready for ritual use.

Before I obtained and read the Diary of Merer myself, I had initially accepted Tallet's interpretation that casing stones were being transported in Year 27. Even then, I found it difficult to imagine that Khufu was still alive at Stage C, when casing stones were still being moved, and that he survived long enough to witness Stage F. I therefore suspected that Khufu's death occurred during Stage D or E. Since the king's burial required the handover of the pyramid and mortuary temple to the priesthood, I questioned whether the structure could have functioned as a funerary complex in the condition represented by Stages D or E. I also considered the possibility that only the two solar boats had actually been completed and ritually consecrated, which would explain why they bear the name of Djedefre and why they survived later destruction or reuse—they were functioning religious installations.

However, after reading the Diary of Merer myself, I found that much of Tallet's interpretation rests on assumptions rather than firm evidence. In particular, the identification of the site as Tura and the assumption that Merer was transporting stone blocks seem weakly supported. Moreover, Tallet's argument presupposes the biennial cattle-count system, yet this system was not definitively established even in William S. Smith's Inscriptional Evidence for the History of the Fourth Dynasty (1952), and scholars such as Zahi Hawass explicitly reject it. Thus, the claim that casing stones were being transported in Year 27 cannot be regarded as securely proven.

Tallet argues that if Year 27 corresponded to Stages A or B, completion would have been impossible, and therefore he places Merer's diary in Stage C, even calling it "the very end of Khufu's reign." Yet if Stage C represents Khufu's final years, it is implausible that he lived long enough to reach Stage F. It is possible that Tallet simply equates the completion of masonry with overall completion.

If we set aside Tallet's assumption that Merer was transporting casing stones, and instead consider that he may have been transporting other goods—supplies, food, or personnel—and if we read the diary as Year 14 rather than Year 27, then Merer's deliveries to the harbor at Giza could

correspond to any stage from A through E. If Stage E corresponds to Year 14, then Stage F occurring around Year 20 would not be unusual. Thus, the interpretive framework I initially adopted—based on Tallet's reading—loses its foundation.

In its place, however, the present condition of the pyramid's summit offers a compelling alternative explanation: if Khufu died during Stage C and construction was abandoned at that point, many of the puzzling features of the summit are naturally accounted for.

The discussions in the following chapters are written with the possibility in mind that Khufu's pyramid remained unfinished. Without this premise, the interpretations that follow would not hold. The purpose is to demonstrate the explanatory power of the unfinished-pyramid hypothesis.

Column 5. Reflections on Royal Names Preserved on Stone

Fig. C5-1 reproduces the inscriptions found on stone blocks from the pyramids of Giza and Dahshur as published in Lepsius's work. Because the original layout is highly irregular, I have prepared Fig. C5-2, in which the signs are resized for comparison. Signs a–e are from Giza, while f and g are from Dahshur.

Among these, a and b represent the standard orthography of King Khufu's name: . Sign c is less commonly attested, and sign d is not immediately recognizable as any known royal name. However, from the perspective of someone accustomed to writing logographic characters, the right-hand element of d appears to be an attempt to imitate the jar sign seen in c. The quadruped on the left, however, is difficult to identify.

Turning to Lepsius's sign C5-2-e, careful inspection reveals that the figure is printed upside down—an editorial error. When rotated 180 degrees (C5-2-e2), it becomes clear that this sign also represents the same sequence. Within this panel, two legible details can be extracted: e3, a cartouche accompanied by the same group of signs seen in c, and e4, a cartouche alone.

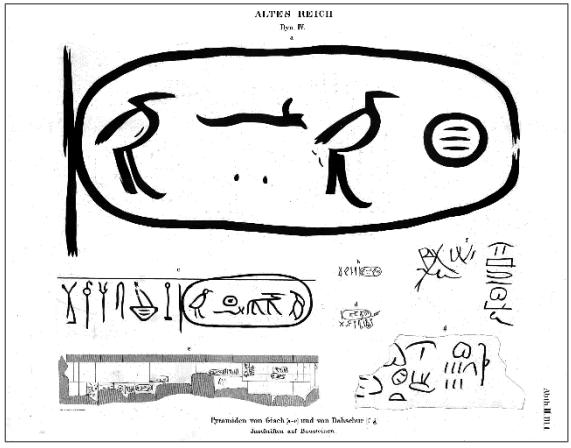
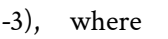
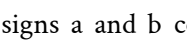


Fig. C5-1. Various royal name inscriptions as published in Karl Richard Lepsius, Denkmäler aus Aegypten und Aethiopien, 1849–1859, Abteilung II, Blatt 1 (Public Domain Mark 1.0, via Internet Archive).

Consulting the website PHARAOH.SE, which compiles numerous variants of royal names, I found that Khufu's name is also written as . The signs represent the god Khnum, associated with water and the Nile; the name thus means "Khnum protects me."

Lepsius also includes a relief from Wadi Maghara in the Sinai Peninsula (C5-3), where the sequence  appears. Consequently, signs a and b correspond to  ; signs c and e3 correspond to ; sign e4 represents , lacking and ; and sign d contains only . In other words, all signs a–e represent variants of Khufu's name.

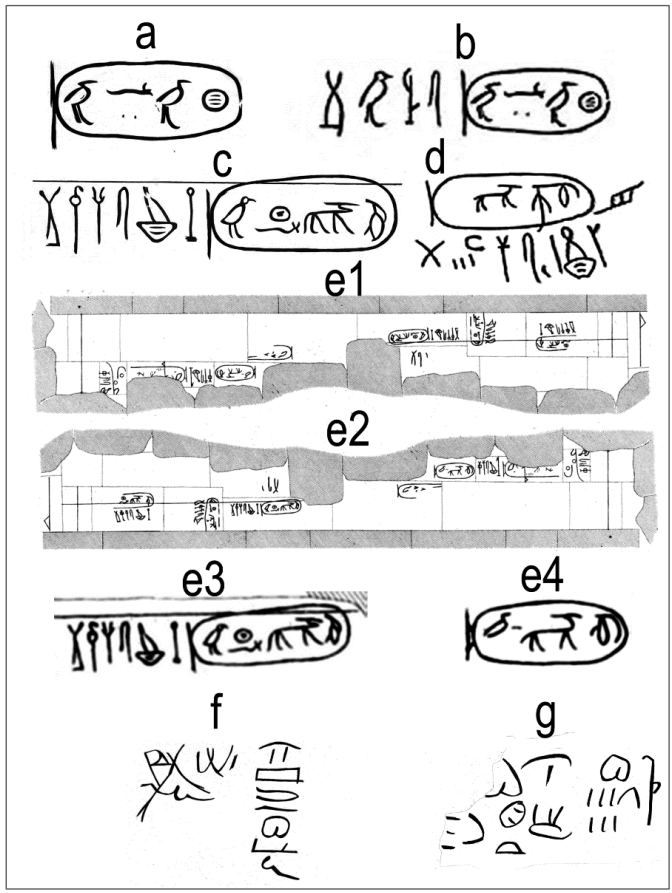


Fig. C5-2. Rearranged and rescaled version of Fig. C5-1 for improved legibility.

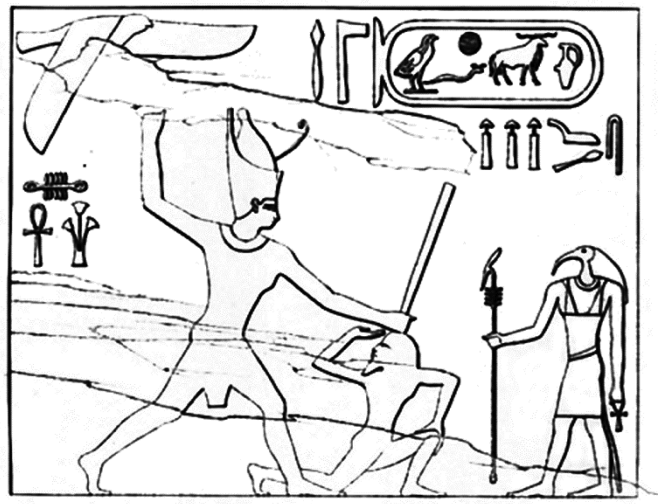
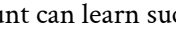


Fig. C5-3. Relief discovered at Wadi Maghara, as published in Lepsius, Denkmäler aus Aegypten und Aethiopien, 1849–1859, Abteilung II, Blatt 2.

In logographic writing systems, it is possible to imitate the shape of characters without understanding their meaning. In Japan, for example, kindergarten-aged children often attempt to copy kanji by sight, even though they cannot read them. Although literacy in ancient Egypt is often estimated at around one percent, I believe that numeracy was far more widespread—perhaps ten percent of the population could read and write numbers. After all,  simply represents "368"; anyone who can count can learn such numerals.

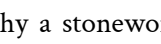
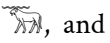
If you now look at sign C5-2-g, you will immediately recognize that the numerals 16 and 13 are clearly written there.

The inscriptions on the pyramid stones include work-gang names and what appear to be placement numbers. Among those who wrote these marks, some were literate and capable of writing signs correctly—such as the scribes responsible for a, b, and c—while others merely copied the shapes. Those who copied the signs may not have understood hieroglyphs or been able to read them aloud, but they could still imitate the drawings.

長瀬　博之

Nagase　Hiroyuki

To illustrate this, I would like readers to try copying my own name—Nagase Hiroyuki (長瀬博之)—five times by sight. For the first attempt, please try writing the full 長瀬博之. If this proves too difficult, you may write only 博之 for the remaining attempts; even I find the character 瀬 cumbersome to write in daily life.

After completing five attempts, you will likely find that no two copies are identical. The fifth 博之 you wrote is probably far closer to the original than the first attempt. At this point, you may also understand why a stoneworker might have wished to abbreviate  to  , and why omissions such as that seen in e4 occur. Copying a drawing is not the same as writing a character.

It is therefore plausible that the Dahshur inscriptions f and g were not written as hieroglyphs but drawn as pictures. Their irregular arrangement and the completely unidentifiable sign on the left side of f suggest that the writer did not understand the script itself.

CHAPTER 10

The Discontinuity of King Djedefre's Pyramid

1. The Abrupt End of the Large-Pyramid Tradition

King Djedefre abandoned Giza and built his pyramid at Abu Rawash, approximately eight kilometers to the north. Dr. Mark Lehner has explained this relocation as a religious decision, noting that Djedefre was the first king to adopt the title "Son of Ra," and suggesting that Abu Rawash—being closer to Heliopolis, the center of the solar cult—was chosen for theological reasons. I do not reject this interpretation. However, several features of Djedefre's pyramid indicate changes that cannot be fully explained by religious motivations alone.

The first major discontinuity is the abrupt end of the large-pyramid tradition that had continued for roughly fifty years since the reign of Sneferu.

Although Djedefre's pyramid now survives only as a mound of rubble, long-term excavations by the French–Swiss mission have determined that its base measured 106 meters, with an estimated slope angle between 48° and 52°, implying a height of approximately 57 to 67 meters.
(Michel Valloggia, Le complexe funéraire de Rêdjédef à Abou-Rawash : état des travaux après dix campagnes (1995–2004), Bulletin de la Société

Fig. 10-1. Transition from Sneferu's first true pyramid to Djedefre's pyramid (drawn to identical scale)

française d'égyptologie, no. 161, 2004, pp. 12–27.)

Fig. 10-1 illustrates the progression from Sneferu's first true pyramid at Meidum to Djedefre's pyramid. The hypothetical outline of the Meidum pyramid on the left is based on Petrie's reconstruction, while the form of Djedefre's pyramid on the right is drawn from the French–Swiss mission's measurements. As the figure makes clear, the trend toward increasingly large pyramids—Meidum, Bent, Red, and Khufu—was suddenly broken, and the scale was drastically reduced.

Petrie measured the Meidum pyramid's slope at 51.5 degrees and its base at 144 meters, giving a height of roughly 90 meters. If we adopt a convenient slope of 50 degrees for Djedefre's pyramid (within the French–Swiss team's estimated range), Meidum's volume is 622,080m^3, whereas Djedefre's is only 236,500 m^3—merely 38 percent of Meidum's volume.

This reduction in scale also appears in the reign of Menkaure, leading to popular explanations that attribute the change to "national exhaustion." However, the actual resource and labor burden of pyramid construction varied greatly depending on the stage of the project, making such explanations unsatisfactory. The evidence suggests a shift in values rather than simple economic decline.

One striking example is the use of red granite as casing stone. Red granite had to be transported from Aswan, roughly 1,000 kilometers upstream along the Nile. Because granite cannot be worked with copper tools, quarrying, transport, and dressing would have required far greater labor than limestone. If the reduction in pyramid size were due to labor shortages, the adoption of red granite would contradict that explanation. The choice may reflect an ideological shift—perhaps even an aesthetic concept such as a two-tone exterior of red below and white above.

The internal structure of the pyramid, however, shows an even more dramatic departure from earlier designs.

Fig. 10-2 reproduces the cross-section (Fig. 3), plan of the trench (Fig. 2), and north–south section of the trench (Fig. 4) recorded by Howard Vyse and Perring. Because the dimensions in these figures do not perfectly match, the values should be regarded as approximate, with an

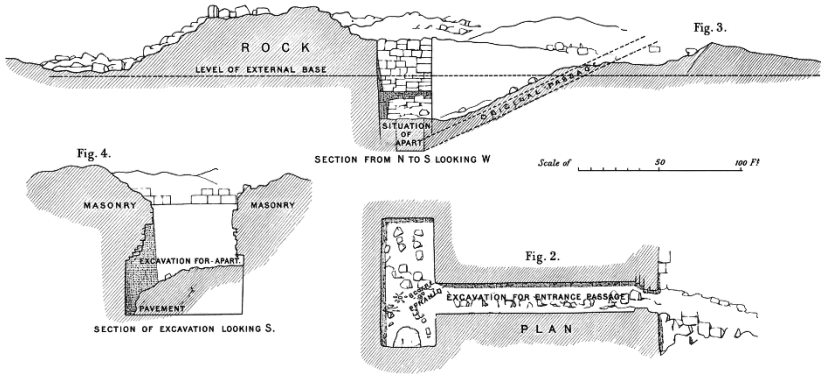


Fig. 10-2. Cross-section and trench diagrams of Djedefre's pyramid (traced from Howard Vyse, Operations Carried on at the Pyramids of Gizeh, vol. 3)

error margin of about five percent. Based on the scale in the drawings, the trench measures 34.6 feet (10.5 m) in width at the top, 74.1 feet (22.6 m) in length, and 66.6 feet (20.3 m) in depth—a massive cavity.

This trench was excavated downward from the top of the limestone bedrock. Its scale raises fundamental questions: Was it intended to be roofed with massive ceiling stones to form a burial chamber? Or was it meant to be filled in before the pyramid's masonry began? The dimensions exceed those of Khufu's King's Chamber (10.5 × 5.2 m, height 5.8 m), making it difficult to imagine how such a vast space could have been roofed and then built over with pyramid masonry. If the trench was intended to be filled, its purpose becomes even more obscure.

The trench appears to have served a function different from that of a conventional burial chamber.

Furthermore, the French–Swiss mission reports that the bedding surface of the granite casing stones inclines inward by approximately 12 degrees. After the structural crisis of Sneferu's Bent Pyramid, both the Red Pyramid and Khufu's pyramid adopted horizontal courses. The return to inward-leaning masonry in Djedefre's pyramid is therefore puzzling.

The number and magnitude of these discontinuities cannot be explained merely by a change of construction site. They suggest a deeper

transformation: a shift in the conceptual basis of pyramid construction, a deliberate break with the architectural tradition of Khufu's reign, or perhaps both.

2. Djedefre's Response to an Unfinished Khufu Pyramid

If Khufu died while his pyramid was still under construction—whether during the masonry stage or before the casing and ramp removal were completed—and if the project was subsequently abandoned, one must consider how Djedefre responded as his successor.

If construction ceased prematurely, the massive ramps built for transporting stone would have remained encircling the monument, leaving the site in the condition of an unfinished civil-engineering project. Removing these ramps would have required enormous labor.

In ancient Egypt, most unfinished projects were simply abandoned. Although a few cases appear to show successors completing predecessors' monuments, such instances are rare and often involve extending or repurposing existing structures—more akin to redevelopment than to completing an inherited project. In my research, I have found no evidence that any pyramid of the Old Kingdom, up to the Sixth Dynasty, was completed by a successor.

Although Giza today contains the pyramids of Khafre and Menkaure and numerous mastabas of high officials, at the time of Khufu's death the plateau may have been sparsely developed, dominated by an abandoned and incomplete construction site. Djedefre may therefore have avoided Giza not only for religious reasons but also because the location had become undesirable—perhaps even inauspicious—due to the failure of his father's monumental project.

If Khufu's pyramid remained unfinished after more than twenty-seven years of work, and if Khufu himself was not buried within it, then Djedefre, having witnessed this outcome, may have been reluctant to attempt another massive pyramid. His decision to build a smaller pyramid at Abu Rawash becomes understandable in this light.

CHAPTER 11

The Pyramid of King Khafre

1. The Return to Giza

King Djedefre relocated the royal pyramid project from Giza to Abu Rawash. Yet under his successor, King Khafre, construction returned to Giza, where a new large pyramid—comparable in scale to that of Khufu—was initiated. Whether Khafre himself ardently desired to build such a massive pyramid cannot be stated with certainty, but given the magnitude of the undertaking, his personal approval must have been indispensable.

In Chapter 10, I noted that Djedefre's pyramid appears to reflect a design philosophy distinct from the horizontal masonry and safety-oriented engineering seen in the Red Pyramid and Khufu's pyramid. This observation may be more significant than it first appears. During the fifty years from Sneferu to Khufu, not only did a technical tradition develop—especially after the "bending" of the Bent Pyramid—but a large community of craftsmen, quarry workers, polishers, transport crews, overseers, and high-ranking officials also emerged. Their livelihoods, status, and authority had been sustained by the large-pyramid program for half a century. Under Djedefre, many of these individuals may have found themselves marginalized.

If Khafre expressed interest in constructing a massive pyramid, it is likely that these groups strongly supported the initiative.

Although it is difficult to apply modern political logic to ancient Egypt, where the king was regarded as divine, even a king's ambitions required the backing of a vast bureaucratic apparatus. The desire of these groups

Fig. 11-1. The Pyramid of King Khafre and the Sphinx (photographed in January 2025).

to revive the large-pyramid project may have formed an important foundation for Khafre's decision.

However, Khafre and the ruling elite must also have been aware that Khufu's pyramid had suffered major delays. Whether the construction period could be shortened was undoubtedly a central question.

One of the reasons I suspect that Khufu's pyramid remained unfinished is precisely that Khafre approved the construction of another giant pyramid at Giza.

From the perspective of the pyramid-building community, Giza offered far better conditions than Abu Rawash, where only a small pyramid had been built. Even after eight years of abandonment, the infrastructure for large-scale construction at Giza would have remained largely intact. The plateau also had a proven record of bedrock stability.

If Khufu's pyramid had been abandoned during the construction of its 204th course, the mudbrick scaffolding and spiral ramps would still have

surrounded the structure. These materials could have been reused, significantly reducing the preparatory phase of Khafre's project.

Moreover, the causes of delay in Khufu's pyramid must have been thoroughly analyzed. It would have been natural to assume that eliminating the factors responsible for the prolonged construction—excessive safety design and repeated trial-and-error—would allow for a shorter timeline. In modern manufacturing, reducing labor hours through design and process revision is routine; the same logic would have applied here.

During Djedefre's eight-year reign, generational turnover among the pyramid-building workforce must also have occurred. Given that adult life expectancy in ancient Egypt was only twenty to thirty years, eight years would have been sufficient for older members of the Khufu-era workforce to be replaced by younger ones. The generation that had emphasized extreme safety measures during the Red Pyramid period would have largely disappeared, and younger, more flexible engineers likely assumed leadership roles. This shift would have encouraged a transformation in design philosophy.

The primary cause of delay in Khufu's pyramid was excessive safety design combined with repeated experimentation—technical factors above all. Thus, in designing Khafre's pyramid, construction speed was likely the highest priority, and Khufu's over-engineered and overly cautious methods were probably revised.

If technical improvements made a shorter construction period feasible, then building another giant pyramid adjacent to Khufu's would have been entirely rational. The bedrock at Giza had already proven capable of supporting a massive structure, and the site offered the advantage of locally quarried limestone.

I also propose another possibility. If Khufu's pyramid had been abandoned during the casing stage, the enormous ramps used for transporting casing stones would still have existed, and large quantities of unpolished casing stones would have remained on site. For Khafre, this would have been an extremely attractive resource. With both core blocks and casing stones available for reuse, Giza would have been the most

rational construction site.

One might naturally ask: Would Khafre really have used his father's pyramid as a source of building material?

The two solar boats—constructed from highly valuable imported cedar from Lebanon—were not reused, even though they had been disassembled into timber. Because the solar boats had already been consecrated and transferred to the priesthood, they were treated as sacred installations, regardless of their practical value. The pyramid, however, though monumental, would have been regarded as an unfinished structure lacking religious consecration. From this perspective, Khafre may have felt little hesitation in reusing its materials.

Another important point is that Khafre did not succeed Khufu directly. His reign followed the eight to ten years of Djedefre, who had entirely abandoned Giza. Although Khafre was Khufu's son by blood, he was the third king in the sequence.

For these reasons, I believe Khafre's return to Giza was not merely an expression of youthful ambition but a rational decision based on the conviction that a giant pyramid could indeed be completed through improved efficiency.

In the following sections, I will analyze the differences in design philosophy between the pyramids of Khufu and Khafre.

2. The Design Philosophy of Khafre's Pyramid

Although Khufu's pyramid and the pyramid built subsequently by King Khafre are nearly identical in size and external form, their internal structures differ markedly. The underlying design philosophies are fundamentally distinct.

The structural drawings published by the British explorers Howard Vyse and John Shae Perring reveal that Khafre's pyramid is astonishingly simple compared with that of Khufu. The interior of Khafre's square-based pyramid is essentially solid masonry, with the core filled entirely with stone.

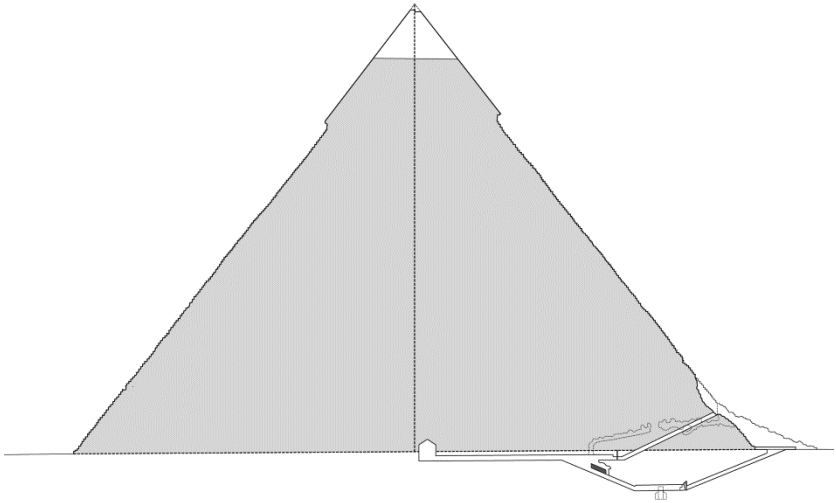


Fig. 11-2. Internal structure of the Pyramid of King Khafre (traced from Howard Vyse, Operations Carried on at the Pyramids of Gizeh)

The most striking feature of this diagram is that the burial chamber is half-embedded in the bedrock, with the upper half originally exposed at ground level—or at least situated close enough to the surface that it was excavated downward from above. Unlike Khufu's pyramid, Khafre's pyramid lacks a gravity-relieving system; instead, a simple gabled ceiling stone rests directly over the chamber.

There are two entrances, and two distinct routes converge partway toward the burial chamber. The horizontal passage leading to the chamber lies near the interface between bedrock and ground surface. It appears that not all of this passage was tunneled through solid rock; rather, portions were quarried open from above and then roofed with ceiling stones. This method—using the bedrock as sidewalls while avoiding the difficulty of full tunneling—was far more efficient and highly rational.

Given such a straightforward internal structure, and considering that casing stones still survive near the summit, the overall preservation of Khafre's pyramid is superior to that of Khufu's. For this reason, I initially

assumed that the design philosophy must have been excellent, and that the quality control of stonework and construction must likewise have been exemplary.

However, upon consulting the literature, I encountered assessments that contradicted my expectations. Petrie notes that, in contrast to the precisely finished stones of Khufu's pyramid, the blocks of Khafre's pyramid are irregular in shape and frequently packed with mortar. Wieser claims that the pyramid was built atop a rocky hill to save stone.

This was unexpected. Yet Wieser's assertion that the pyramid was built on a high hill to conserve stone is poorly supported. If the hill had been high enough to significantly reduce the volume of masonry, a deep vertical shaft would have been required to install the gabled ceiling of the burial chamber. Moreover, although Wieser and Perring belonged to the same survey team, Perring's own published diagrams depict a relatively flat bedrock surface, contradicting Wieser's interpretation.

Petrie's observation, however—that Khafre's masonry is noticeably less regular than Khufu's—matches my own impressions from walking around the Giza pyramids over two days in 2008. Anyone who compares the two structures on site will immediately recognize the difference. Relative to the crisp, orderly masonry of Khufu's pyramid, Khafre's stonework is indeed less uniform.

Moreover, Petrie's observation—that, in contrast to the precisely finished blocks of Khufu's pyramid, the stones of Khafre's pyramid are

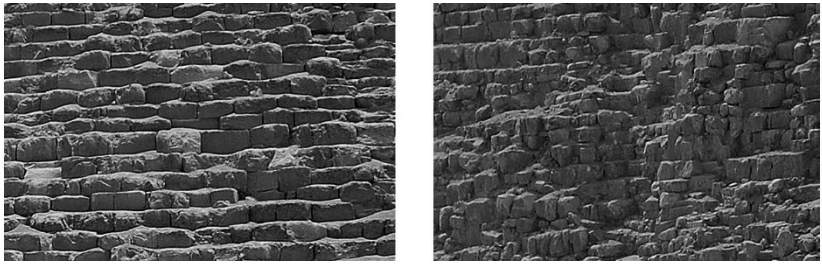


Fig. 11-3. Masonry of the Pyramid of Khufu (left) and the Pyramid of Khafre (right), both photographed in August 2008.

Fig. 11-4. Close-up view of the upper portion of the Pyramid of King Khafre (photographed in 2025).

irregular in shape and frequently packed with mortar—was something I had already noticed during my two-day survey of the Giza pyramids in August 2008. Anyone who compares the two structures on site will immediately recognize the difference; relative to the crisp and orderly masonry of Khufu's pyramid, Khafre's stonework is indeed less uniform.

Although the dimensions of individual blocks are not perfectly consistent in either pyramid, Khufu's masonry clearly consists of limestone blocks that were shaped, at least in principle, into rectilinear forms before being laid. In contrast, the blocks of Khafre's pyramid lack uniformity in both shape and size, producing an impression of instability. In earthquake-prone Japan, the perimeter of such a structure might well be cordoned off as a hazard zone, so precarious does it appear.

However, when I examined photographs taken during my return visit in January 2025, I noticed that the stones directly beneath the surviving casing blocks near the summit appear to be worked with care comparable to that seen in Khufu's pyramid. This suggests that the uppermost courses may have been executed with greater precision than the lower ones.

Nevertheless, it would be premature to conclude—based solely on the present appearance of the masonry—that Khufu's pyramid was categorically superior to Khafre's. Both structures have survived for

4,500 years, and Khafre's pyramid retains a substantial portion of its casing stones near the summit. This fact alone cautions against simplistic judgments based solely on the current condition of exposed masonry.

3. The Evolution of Internal Pyramid Structures

Among the pyramids of the Third Dynasty, the largest—the Step Pyramid of King Djoser—is renowned for its extraordinarily complex subterranean architecture, resembling an underground palace. The unfinished step pyramids of Sekhemkhet and the so-called "layer pyramid" attributed to Khaba also employed underground burial chambers.

In contrast, Sneferu, founder of the Fourth Dynasty, constructed the burial chamber of his Meidum pyramid (Fig. 11-5-A) near the interface between bedrock and ground surface.

The internal structure of Sneferu's subsequent Bent Pyramid (11-5-B) shows a period of experimentation. The initial plan involved a descending passage leading to an underground burial chamber. However, the inward-leaning masonry of this large pyramid produced substantial vertical pressure along the central axis, and combined with the fragile bedrock at Dahshur, caused damage to the subterranean chamber. As a result, the burial chamber was relocated upward into the core of the pyramid. This modification must have occurred early in construction, before the masonry had risen significantly; carving a chamber into a completed core would have been extremely difficult and structurally hazardous.

In the Red Pyramid (11-5-C), the burial chamber was built entirely above ground. After the "failure" of the Bent Pyramid, the new project team likely abandoned the idea of subterranean chambers altogether. Because both the Bent and Red Pyramids employed corbelled ceilings, their chambers could not be wide, resulting in long, narrow, corridor-like spaces.

With Khufu's pyramid (11-5-D), however, the concept of the burial chamber changed dramatically.

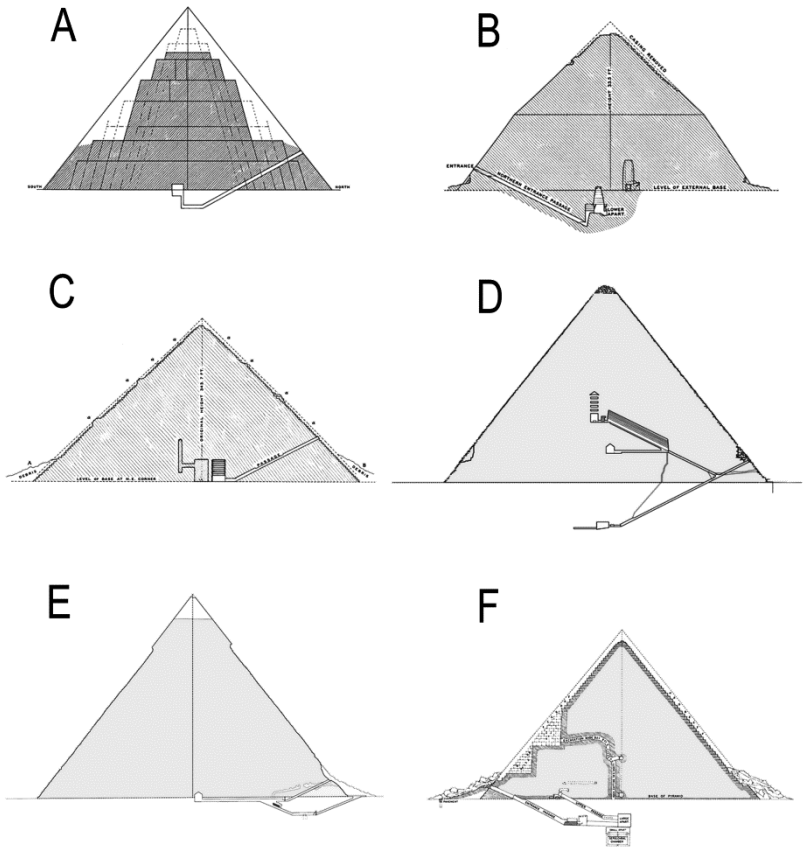


Fig. 11-5. Internal structures of the Fourth Dynasty pyramids (based on the structural diagrams of Perring and Petrie; scales of individual pyramids are not uniform).

The unfinished subterranean chamber of Khufu's pyramid appears to have been an attempt to revive the Third Dynasty tradition of underground burial chambers. Although such chambers had proven problematic at Dahshur due to weak bedrock, the strong limestone plateau at Giza made the idea reasonable. Yet the subterranean chamber was never completed.

The pyramid's steep slope of 52 degrees and design height of 146 meters must have created constant anxiety regarding vertical

gravitational load. To mitigate this risk, the builders appear to have conceived an innovative idea absent from earlier pyramids: placing the burial chamber higher in the structure, where vertical load would be reduced. The first attempt at an internal chamber was the Queen's Chamber. After observing deformation or cracking—or the absence thereof—the builders likely judged the chamber safe and proceeded to construct the higher King's Chamber.

Even so, concerns about vertical load from the pyramid's mass persisted, leading to the adoption of the King's Chamber's complex gravity-relieving system. In other words, Khufu's pyramid seems to have been designed with the intention of "escaping upward," relocating the burial chamber progressively higher as construction advanced.

Khafre's pyramid (11-5-E) also appears initially to have been planned with a subterranean chamber, but this idea was soon abandoned. The final chamber was placed near the surface of the bedrock. Its walls incorporate the natural rock, while the gabled ceiling was installed either on exposed bedrock or on bedrock quarried downward. The design philosophy resembles that of Sneferu's Meidum pyramid.

In Menkaure's pyramid (11-5-F), the subterranean chamber was revived once again.

Thus, even among pyramids that appear externally similar, the internal design philosophy fluctuated continuously.

Khufu's pyramid is particularly unusual within the Fourth Dynasty: its burial chamber was placed high within the masonry core, far above the bedrock. Khafre's pyramid, by contrast, returned to a more orthodox approach.

Khufu's builders trusted the strength of the Giza bedrock, yet the unprecedented slope of 52 degrees and design height of 146 meters must have produced persistent fear of vertical load and ground pressure. I believe this anxiety manifested in the pyramid's complex internal structure. Khafre's pyramid, on the other hand, reflects a design philosophy grounded in confidence that "the bedrock is sufficiently strong."

As an aside, although the internal structures of these pyramids vary

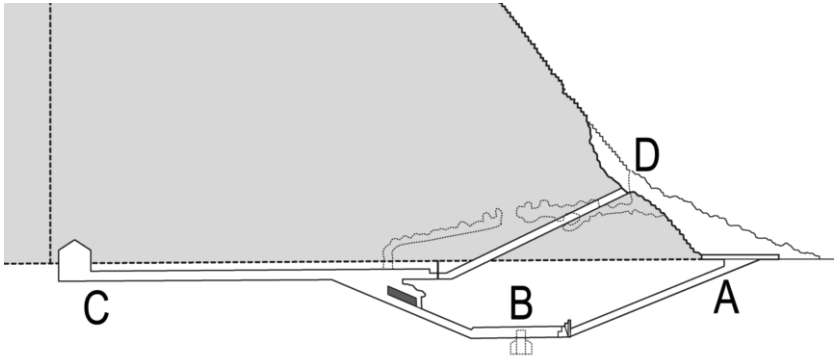


Fig. 11-6. The two passageways of the Pyramid of King Khafre (traced from Perring's structural diagram).

widely, their passage slopes cluster around 26 degrees—a striking pattern. This is unlikely to be coincidental. In ancient Egyptian units of slope (the seked), a ratio of 2 horizontal to 1 vertical corresponds to 26.56 degrees. This simple ratio may have made design and construction easier, explaining the consistent use of this angle.

4. The Burial Chamber of King Khafre

It is reasonable to assume that, in constructing Khafre's pyramid, the builders conducted geological investigations to confirm the strength of the bedrock, and that an underground burial chamber—similar to that planned for Khufu—was initially contemplated.

Section 11-6-A shows the descending passage leading underground. Today, this passage serves as the entrance used by visitors to access the interior of the pyramid. The passage slopes downward and reaches a depth of approximately 20 meters, where it transitions into a horizontal corridor leading to point B. At B, a small chamber was constructed, and a vertical shaft was cut into its floor. This feature closely resembles the subterranean chamber of Khufu's pyramid.

I believe this descending passage originally served as a preliminary exploratory shaft, intended to assess the thickness, quality, and uniformity

of the bedrock before full construction commenced. At the time excavation began, the plan likely included not only this exploratory shaft but also a large subterranean burial chamber extending from the horizontal section at B—essentially following the same conceptual model as Khufu's pyramid.

However, the underground chamber was never built. The actual burial chamber is a "semi-subterranean" structure, created by quarrying downward from the bedrock surface. This interpretation is consistent with descriptions by Dr. Mark Lehner and by Maragioglio and Rinaldi in L'architettura delle piramidi menfite – Parte IV: La Grande Piramide di Cheope.

The reason for abandoning the subterranean chamber in favor of a semi-subterranean one remains unclear.

Nevertheless, if Khufu's subterranean chamber had functioned as a monitoring post—confirming that no anomalies existed within the bedrock—and if the vertical shaft at B provided sufficient information regarding bedrock thickness and quality, then the builders may have concluded that the bedrock at Khafre's site was comparable to that at Khufu's. This would justify the decision that "the bedrock is sufficiently reliable."

This conclusion appears to be supported by the placement of the burial chamber and its horizontal access passage: both lie just below the bedrock surface. This configuration allowed for easy quarrying from above, avoided constructing a chamber entirely within the masonry core, and ensured that vertical loads on the passage and chamber were borne by the surrounding bedrock rather than by the pyramid's masonry. The location is, in this sense, structurally optimal.

Furthermore, the gravity-relieving structures so prominent in Khufu's pyramid are almost entirely absent in Khafre's. The only comparable feature is the gabled ceiling of the burial chamber.

Recent muon-radiography investigations of Khafre's pyramid have not revealed any large internal cavities, further supporting the interpretation that no additional chambers exist above the burial chamber.

CHAPTER 12

Considerations on the Two Passageways of Khafre's Pyramid

1. The Two Passageways

The passage extending from point C to point D in Fig. 11-6 was likely constructed progressively as the pyramid's masonry rose. In other words, access between the ground level and point C must have been maintained throughout construction, meaning that movement to and from C would have posed no difficulty

At this point, however, I encountered a new question: For what purpose was the ascending passage from B to the horizontal passage at C constructed?

Although many researchers have noted the existence of the two passageways and have proposed explanations for their apparent inconsistency, none of these arguments seemed sufficiently convincing to me. Khafre's pyramid exhibits rational design choices in many respects, making the seeming irrationality of the dual-passage system particularly striking.

While surveying various sources, I came across the account of Giovanni Battista Belzoni, the first explorer to reach Khafre's burial chamber.

By 1818, when Belzoni began searching for the entrance to Khafre's pyramid, both the official and the robber's entrances of Khufu's pyramid were already known. Belzoni therefore examined the central axis of the northern face of Khafre's pyramid, and—knowing that Khufu's entrance lies slightly east of the axis—he also investigated that area. He removed the debris covering the pyramid's face until much of the masonry was

exposed. After more than two weeks, he discovered a robber's tunnel, but it was dangerously unstable, and he abandoned excavation. He failed to locate the true entrance.

Belzoni wrote that "recent disappointments had made me obstinate," and he resolved to continue. Eventually, he discovered the entrance to the descending passage (A). He notes that the workers assisting him had begun calling him a "madman."

Removing large granite blocks and debris from the passage, and lifting a fallen portcullis stone just enough to crawl beneath it, Belzoni finally reached the burial chamber (C) on 2 March 1818. The chamber, however, was empty.

Belzoni had noticed the upper passage while traveling from the descending passage toward the burial chamber, but his priority was to reach the chamber itself. Only afterward did he begin clearing debris from the ascending passage from within the pyramid. The passage had a slope of 26 degrees. Through this work, he discovered that a second passageway existed above the descending one.

Belzoni's account states that after excavating the upper passage from the inside, he reached what he identified as the second entrance (D). It is unclear whether he broke through to the exterior solely from within, or whether he and his team also excavated from the outside based on predicted alignment. Belzoni was conducting measurements and calculations during excavation, so he likely understood where the upper passage would emerge on the pyramid's face.

In summary: Belzoni initially failed to locate D. After various attempts, he discovered A. He then reached the burial chamber at C, identified the ascending passage, cleared it from within, and eventually reached the northern face at D—realizing only then that this was the original entrance. The fact that D was discovered from the inside is crucial.

Another point of interest is the condition of the masonry near D in Petrie's sectional drawing. The area above the passage is heavily hollowed out, and the lower portion is filled with debris.

In Fig.12-1, the area around the entrance (the vertical opening at F) is

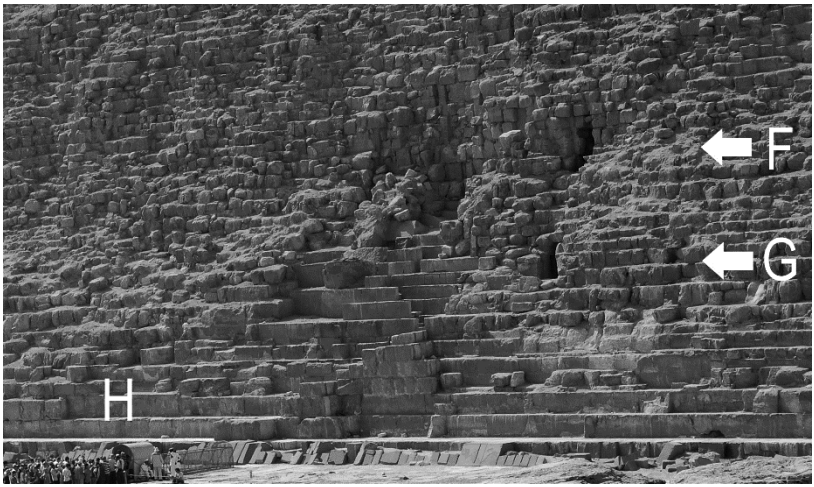


Fig. 12-1. Collapsed area near the entrance of Khafre's pyramid.

significantly hollowed out. Such damage is often attributed to tomb robbers, but I questioned this assumption. Robbers excavated from below (point G), so it is difficult to attribute the upper hollowed-out area to their activity.

The group of tourists visible at H marks the entrance to the descending passage.

Comparing Fig. 12-1 with Belzoni's account led me to a hypothesis: The original entrance at D in Fig. 11-6 may have collapsed during Khafre's lifetime, sustaining irreparable damage. To ensure the king's burial, the builders may have excavated the passage from B to C, thereby restoring access from A to C.

This may seem speculative, but it provides a clear rationale for the otherwise puzzling ascending passage from B to C.

2. Examining the Possibility of Collapse in the Upper Passage

The possibility that the northern entrance passage collapsed is not discussed in mainstream scholarship. Yet I found no source that explicitly rejects the possibility either. It appears that the question has simply not

been considered.

Belzoni wrote that the upper passage was completely blocked with stones when viewed from the inside. The floor may have remained intact, allowing him to follow it outward.

Belzoni clearly states that the descending passage (A) had a granite portcullis, which he broke through. In contrast, the upper passage contained only stones of various sizes; he notes that the portcullis stone had been removed.

If the entrance at D had been intentionally sealed after completion and concealed, one would expect Belzoni to have encountered a granite portcullis. The absence of such a feature suggests a different security design—or perhaps that the entrance had collapsed naturally.

In Khufu's pyramid, the passages leading to the burial chamber—excluding the Grand Gallery—are 1.05 m wide and 1–1.2 m high, with flat ceilings. Khafre's passages follow essentially the same construction method.

However, the entrances differ dramatically. Khufu's entrance is protected by two massive gabled ceiling blocks, still intact today.

Khafre's entrance, by contrast, is severely damaged and resembles a

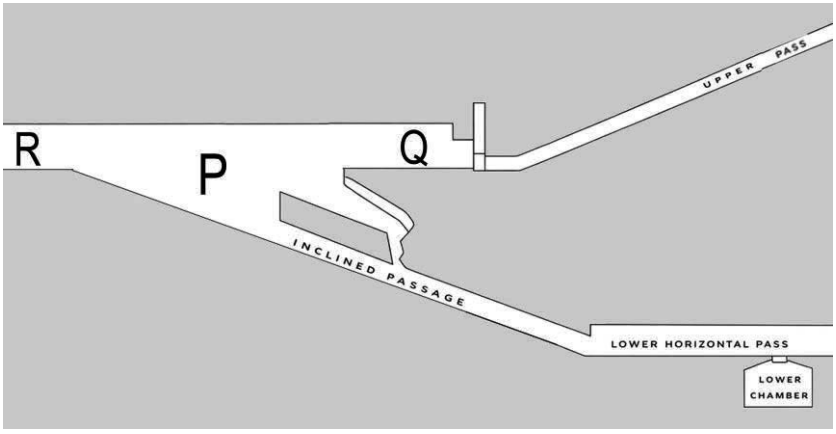


Fig. 12-2. Enlarged diagram of the two passageways of the Pyramid of King Khafre (traced from Perring's structural drawing).

robber's tunnel. No gabled structure is visible. I examined the literature for evidence of a gabled entrance in Khafre's pyramid. If such a structure—comparable to Khufu's—had existed, it would almost certainly have been documented. No such record exists. This suggests that even if a gabled structure once existed, it was far less substantial than that of Khufu's pyramid.

Next, I re-examined the junction between the descending passage and the upper passage using the diagrams. The explanation here follows Perring's original drawing.

Fig. 12-2 is a traced version of Perring's diagram, representing the conditions at the time of his survey (the robber's tunnel is omitted). One point that requires particular attention is the space marked P in Fig. 12-2. Although P appears to be a wide area in the sectional drawing, its actual width is only slightly more than one meter. In other words, it is not a space where ascending and descending traffic could run parallel to each other, like the up-and-down escalators in a department store. Even though the two passages meet at this point, the space could function as only one passage at a time.

This point strongly contradicts the idea that the upper passage connecting Q and R was still in use when the builders excavated

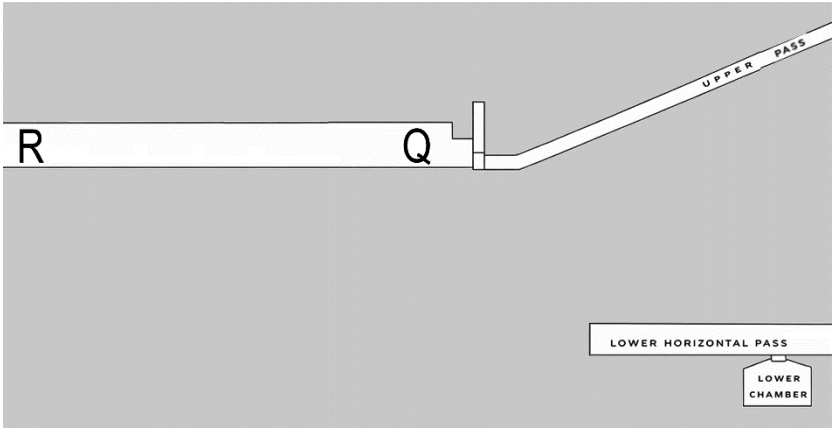


Fig. 12-3. Reconstruction illustrating the upper passageway as it may have appeared when it served as the primary entrance.

downward at P in order to link it with the descending passage.

The moment the area at P was cut downward, the passage at Q would have ceased to function entirely. In other words, the geometry of the junction makes it impossible for both passages to have operated simultaneously during such an excavation.

Fig. 12-3 presents a reconstruction of the situation when the upper passage served as the formal, primary route to the burial chamber. The fact that the ceiling height of the passage at points Q and R is identical strongly suggests that this corridor originally formed a single, continuous passage. In contrast, the descending passage was abandoned after only a short extension beyond the subterranean chamber, once the design of the burial chamber was altered to a location near the bedrock surface. As a result, the descending passage became a dead end and construction was halted.

Fig. 12-4 illustrates the situation after the upper passage had become blocked, prompting the initiation of an emergency excavation of an upward-sloping shaft. From the ceiling of this shaft, a vertical probe was then cut upward, apparently to verify the positional relationship between the shaft and the horizontal passage connecting Q and R. Maragioglio and Rinaldi note that this vertical shaft is finished in a very rough manner,

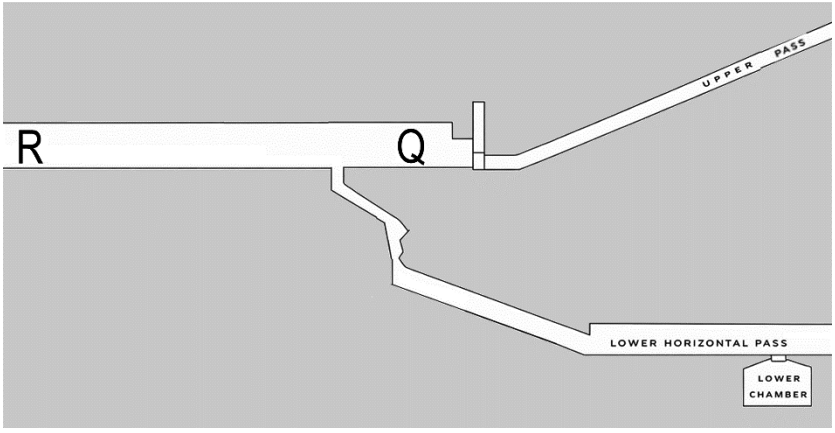


Fig. 12-4. Reconstruction illustrating the beginning of the extension work on the descending passage.

and its form clearly indicates that it was never intended as a formal passage. It is difficult to interpret it as anything other than a test shaft excavated to determine whether reconnection with the upper passage was possible.

Once the test excavation confirmed that the horizontal passage lay directly above the descending passage, the probe shaft was likely enlarged. Fig. 12-5 shows the state of this upward-cut opening after expansion. At this stage, I believe the enlargement was intended to create sufficient working space for clearing the collapsed upper passage from the inside, much as Belzoni later excavated it from within. Such an operation would have required bringing a considerable number of workers and tools into the area around point Q, and the expansion of the opening appears to have been designed to accommodate that need.

However, this attempt at restoration appears to have failed. Once the effort to reopen the upper passage was abandoned, the area marked S in Fig. 12-5 was excavated, and the descending passage was extended toward the burial chamber. This work ultimately produced the present configuration shown in Fig. 12-2.

Thus, although it is reasonable to explain the situation by assuming that the upper passage was constructed first and later became unusable—

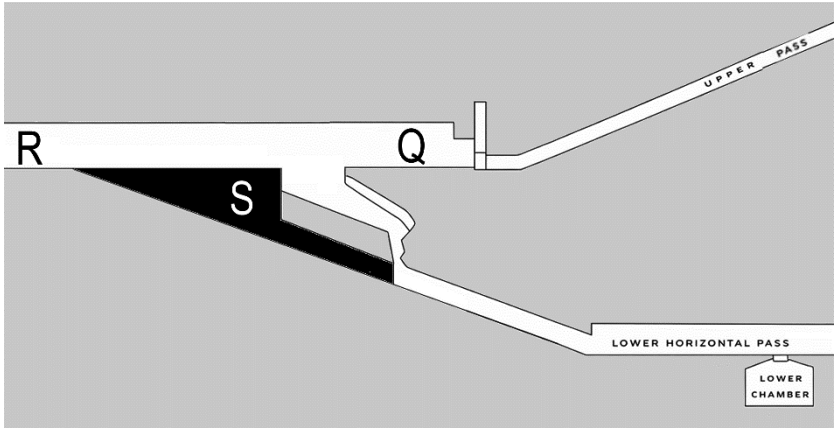


Fig. 12-5. Expansion of the opening connecting the descending passage to the upper passage.

necessitating the extension of the descending passage to reach the burial chamber—it is far more difficult to imagine the opposite sequence: that the descending passage originally reached the chamber and that the upper passage was subsequently connected to it.

Considering the manner in which the two passages join, the apparent lack of a robust gabled entrance structure comparable to that of Khufu's pyramid, and Belzoni's descriptions of the blocked upper passage, it is most plausible that the original entrance collapsed, rendering the upper passage unusable.

3. Considerations on the Impact of the Entrance Collapse

The differences in design philosophy between the internal structures of Khufu's pyramid and Khafre's pyramid have been noted several times already. The seemingly excessive measures taken in Khufu's pyramid to manage vertical and lateral loads were, in Khafre's pyramid, reduced to a far more rational and economical system. The superior precision of Khufu's masonry is one example of this contrast: Khufu's project appears to have implemented every conceivable safety measure, not through selective reasoning but by executing all possible precautions.

For the engineering team that had constructed the Red Pyramid with its extremely safe 43-degree slope, the specifications demanded for Khufu's pyramid—52 degrees and a design height of 146 meters—must have seemed extraordinarily severe. Their response included relocating the project to Giza, conducting extensive bedrock surveys, and developing multiple load-distribution systems, while also insisting on high precision in stone cutting.

In Khafre's pyramid, by contrast, the design philosophy rested on confidence in the strength and stability of the bedrock. Structural simplicity was regarded as the optimal solution. The builders appear to have judged, with sober realism, that certain theoretically beneficial measures—such as extreme precision in stone cutting—were not essential, and that practical, on-site adjustments would suffice. In modern

terms, this could be described as rationalization through the elimination of over-quality. However, no surviving evidence confirms how simplified the entrance structure of Khafre's pyramid actually was, nor can we determine the precise cause of its collapse. What is clear is that the entrance was the only part of the pyramid that appears structurally vulnerable.

If the entrance collapsed, preventing access to the interior, the king could not be buried—a catastrophic situation during Khafre's reign. Such an accident would have made it impossible to continue construction as planned. Consequently, the builders likely undertook excavation from the already obsolete descending passage, extending it until it connected with the burial chamber.

For the engineering team, the accident must have been a highly visible and dramatic failure, one that damaged their authority and credibility. I wish to emphasize that this failure was not the result of negligence or complacency, but rather the unintended consequence of a rationalized design—one that had eliminated certain redundancies and thus exposed a critical weakness.

From a modern perspective, such an event might be expected to undermine royal authority and become a political issue. However, I believe this was unlikely in Khafre's time. The king possessed transcendent authority as a divine figure, and the notion of political accountability is difficult to apply within an absolutist system.

The timing of this "entrance-collapse accident" remains uncertain. If it occurred during the middle phase of pyramid construction—while the masonry was still being laid—the work would have been temporarily halted. However, the extension of the descending passage and the resumption of construction could have proceeded in parallel, and the pyramid would ultimately have been completed. This is because the excavation of the descending passage and the continuation of masonry work could be carried out simultaneously.

By contrast, if the accident occurred near the end of construction—during the final stages of dressing the casing stones, when the removal of

the construction ramps was nearly complete—the consequences may have been far more serious. At such a late stage, the collapse of the entrance would have disrupted not only access to the interior but also the final operations required to finish the pyramid, potentially imposing severe delays and forcing major revisions to the burial arrangements.

CHAPTER 13

The End of the Large Pyramid Construction

1. The Pyramid of King Menkaure

The successor to King Khafre was his son, King Menkaure.

Menkaure also built his pyramid at Giza. The photograph was taken near the so-called "Panorama Point," beside the queen's pyramids associated with Menkaure. Behind the three subsidiary pyramids, one can see—from left to right—the pyramids of Menkaure, Khafre, and Khufu.

This location is known as "Panorama Point" because it offers a distant view of all three pyramids.

Another reason is that, since the photograph is taken from the side of Menkaure's pyramid, Menkaure's pyramid appears visually larger than it actually is.

Fig. 13-1. The Pyramid of King Menkaure (center), photographed in September 2017

In reality, the pyramid of King Menkaure has a base length of 104.6 meters, a height of 61 meters (estimated at 65.5 meters), and an inclination angle of 51 degrees. Compared with the pyramid of King Khufu, its height is less than half, and its volume amounts to only 9 percent of Khufu's pyramid.

Menkaure was not the first to adopt a smaller pyramid after a large one. A similar reduction in scale had already occurred during the reign of King Djedefre, who succeeded Khufu.

There are several similarities between the pyramids of Djedefre and Menkaure—similarities that can hardly be dismissed as mere coincidence. Djedefre's pyramid has a base length of 106 meters, and its inclination angle is thought to have been between 48 and 52 degrees, giving an estimated height of 57 to 67 meters. Moreover, about twenty courses of granite blocks remain at the base of Djedefre's pyramid. In comparison, the lower sixteen courses of Menkaure's pyramid are faced with red granite. Thus, the two pyramids share not only similar dimensions but also the distinctive use of red granite.

The most important point is that, although Djedefre's pyramid has now lost almost all of its original form, if it had been completed, it would still have stood—only about twenty years old—when Menkaure ascended the throne. Since it lies merely 8 kilometers from Giza, its appearance would have been easily visible from the plateau.

Therefore, it seems reasonable to assume that Menkaure did not intentionally choose a uniquely small pyramid; rather, he may have taken Djedefre's pyramid as a model.

However, despite Menkaure's reign being estimated at 18 to 29 years, and thus not particularly short, the red-granite casing at the base of his pyramid remains in an unfinished state, with no cutting or polishing completed.

If one looks only at the prolonged construction process of Menkaure's pyramid, it may suggest a decline in national capacity or project management. Yet, in fact, traces of other large-scale construction works from the late Fourth Dynasty still remain.

Fig. 13-2. The Mastaba of King Shepseskaf (Lepsius, Denkmäler aus Aegypten und Aethiopien, Band I, University of Tokyo General Library, CC BY)

2. The Mastaba of King Shepseskaf

King Shepseskaf, who succeeded Menkaure, is thought to have reigned for only five years.

Yet at Saqqara there stands an enormous mastaba measuring 90 meters in length and 74 meters in width. In Lepsius's nineteenth-century sketch, most of the lower portion is still buried in sand, but today the structure has been excavated: the lowest course retains its red-granite casing, while the upper courses are believed originally to have been faced with limestone.

This two-tone combination of red granite and white limestone appears related to the color scheme of Djedefre's pyramid, a design concept that was later inherited by Menkaure's pyramid.

The question naturally arises whether a monument of this scale could truly have been built within Shepseskaf's five-year reign, and—more fundamentally—why Shepseskaf built a mastaba rather than a pyramid. These questions prompted my own reconsideration of the circumstances.

A plausible interpretation is that Shepseskaf began constructing his mastaba while Menkaure was still alive, having obtained the king's authorization to do so. If Menkaure's reign indeed extended to twenty-nine years, as maintained by the British school, then it would not

be surprising for Shepseskaf—considering his own life expectancy—to wish to begin preparing his tomb. Nor is there any compelling reason to assume that Menkaure would have refused such a request.

Why, then, did Shepseskaf choose a mastaba?

One possibility is that, although Shepseskaf was a son of Menkaure, he was a half-brother of Khuenre, and that Khuenre, as the eldest son of Queen Khamerernebty II, was regarded as the more legitimate heir.

Khuenre's name itself contains the solar deity Ra (☉), placing him in direct succession after Djedefre, Khafre, and Menkaure.

He held the titles "secretary of his father" and "father's sole companion" (Digital Giza, "Khuenre (MQ 1)," Giza Archives, Harvard University–Museum of Fine Arts Expedition). These titles are unlikely to have been given to a mere child; rather, they suggest a high-ranking prince closely involved in the king's personal and administrative affairs. Furthermore, the statue of Khuenre in the Museum of Fine Arts, Boston depicts him in the pose of a scribe, reinforcing the impression that he was not simply a young prince but a figure already entrusted with significant duties and status.

Shepseskaf, at least at the time he planned his tomb, does not appear to have considered the possibility that he might succeed Menkaure as king. Rather, he seems to have been pursuing the path of a loyal vizier serving Menkaure. Conversely, the very fact that Menkaure permitted Shepseskaf to construct a mastaba indicates that, at that moment, Menkaure himself did not regard Shepseskaf as his future successor.

Viewed in this light, Shepseskaf's choice of a mastaba is entirely reasonable. It offers a far more natural explanation than the traditional religious interpretation that sees his choice as a rejection of the solar god Ra.

What, then, of Khuenre?

If Shepseskaf was granted permission to build his large mastaba, it would not be unreasonable to assume that Khuenre was likewise granted permission to build a pyramid. Although no direct evidence survives to confirm that such authorization was given, there exists a massive

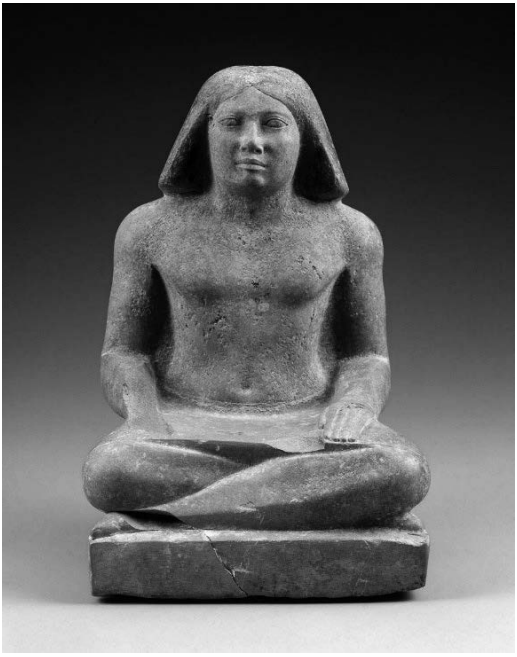


Fig. 13-3. Statue of Prince Khuenre (*Photograph © 2026 Museum of Fine Arts, Boston.)*

unfinished pyramid complex that appears to date to the very end of the Fourth Dynasty.

3. The Unfinished Pyramid at Zawiyet el-Aryan

Approximately 4 kilometers south-southeast of Khufu's pyramid at Giza lies an unfinished structure. Since 1964, the site has been enclosed within an Egyptian military zone, and entry has been prohibited; consequently, no modern archaeological investigations have been carried out.

Despite this, the monument is of extraordinary scale, and it remains enigmatic—particularly with regard to why such a structure was built at Zawiyet el-Aryan, a location that otherwise shows no clear reason for royal construction. Because recent research has been impossible, the site

is seldom discussed in detail today; yet it is a unique and indispensable monument for understanding the pyramid building tradition of the Fourth Dynasty.

The unfinished pyramid was excavated extensively between 1905 and 1912 by the Italian Egyptologist Alessandro Barsanti, then affiliated with the Cairo Museum. After his work, the site was largely abandoned. In the 1950s, however, it was used as a filming location for the American movie The Land of the Pharaohs (directed by Howard Hawks), specifically for the scene depicting the transport of a large stone sarcophagus into the burial chamber.

(As an aside, The Land of the Pharaohs is available online today. From an engineering perspective, several depictions of construction techniques in the film are questionable, yet certain elements—such as the massive mud-brick ramps and papyrus boats—are visually intriguing and worth viewing.)

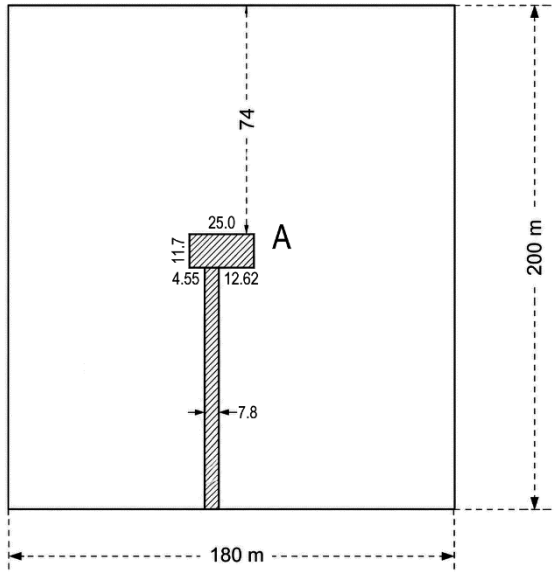


Fig. 13-4. Dimensions of the Unfinished Pyramid at Zawiyet el-Aryan (after Barsanti's plan)(Barsanti, M. Alexandre, "Fouilles de Zaouiet El-Aryan," Annales du Service des Antiquités de l'Égypte, Vol. 7, Cairo, 1906)

Fig. 13-5. Photograph of the structure viewed from direction A in Fig. 13-4 (Barsanti, M. Alexandre, "Fouilles de Zaouiet El-Aryan," Annales du Service des Antiquités de l'Égypte, Vol. 7, Cairo, 1906)

Barsanti regarded the structure as the lowest course of a gigantic pyramid measuring 200 meters north–south and 180 meters east–west, but what draws my particular attention is the enormous subterranean installation that remains.

Descending a 7.8-meter-wide sloping passage, one reaches a massive trench cut into the bedrock, measuring 21 meters in depth, 25 meters in width, and 11.7 meters in length.

This enormous trench had been backfilled with limestone blocks quarried from the site itself, and Barsanti undertook the laborious task of removing these blocks using cranes. Fig. 13-5 is likely a photograph taken during that operation.

The object shown in Fig. 13-6 is an elongated oval basin carved from granite, discovered after the removal of the limestone blocks. Although

Fig. 13-6. Photograph of the bottom of the large trench (Barsanti, M. Alexandre, "Fouilles de Zaouiet El-Aryan," Annales du Service des Antiquités de l'Égypte, Vol. 12, Cairo, 1912)

some have proposed that it functioned as a sarcophagus, there are no parallels for such a form elsewhere, and there is insufficient evidence to identify it definitively as a sarcophagus.

The shape of the enormous trench itself resembles an enlarged version of the rock-cut chamber found in Djedefre's pyramid. It is difficult to imagine that such a vast trench was intended to serve directly as a burial chamber, covered at ground level by long beams and massive ceiling stones. If the structure was meant to function as a chamber, it is more reasonable to assume that the actual chamber was smaller and that the surrounding space was backfilled. In Djedefre's pyramid, no sarcophagus has been found, nor any remains that clearly indicate a burial chamber; this suggests that the large trench there was likewise backfilled before the masonry was laid above it. Whether a subterranean chamber ever existed must therefore be considered with caution.

The trench at Djedefre's pyramid and the trench at Zawiyet el-Aryan appear to share a similar conceptual design, yet because no comparable features exist in other pyramids, their precise function remains impossible to determine.

Nevertheless, the size, form, and two-tone color scheme of Djedefre's pyramid—red granite combined with limestone—were inherited by Menkaure's pyramid. In light of this, it seems plausible that the other distinctive feature of Djedefre's monument, namely its large-scale trench structure, may also have influenced the design of the unfinished pyramid at Zawiyet el-Aryan.

Barsanti recorded the state of the trench when it was still backfilled with limestone blocks, and his drawing clearly illustrates this condition. Judging from the illustration, the larger blocks appear to measure roughly 1 meter in width, 1 meter in depth, and 4 meters in length. Their arrangement suggests that they had been dumped in later, rather than carefully placed. Yet these blocks seem originally to have been quarried from the trench itself.

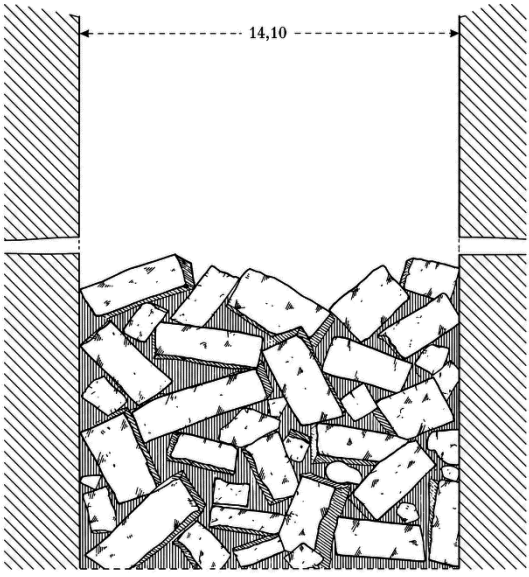


Fig. 13-7. Diagram of the trench backfilled with limestone blocks

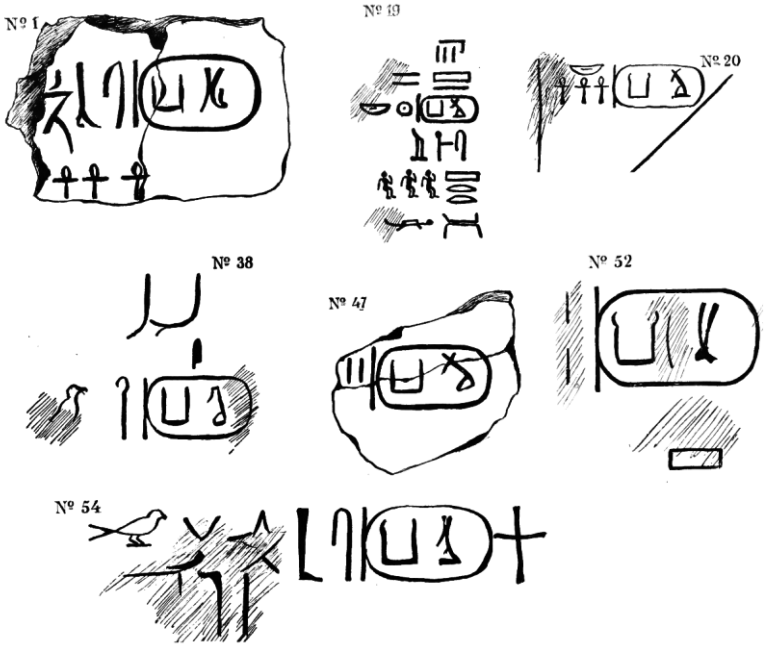


Fig. 13-8. Inscriptions found on the limestone blocks at Zawiyet el-Aryan (Barsanti, M. Alexandre, "Fouilles de Zaouiet El-Aryan," Annales du Service des Antiquités de l'Égypte, Vol. 7, Cairo, 1906)

At Zawiyet el-Aryan, several limestone blocks bearing hieratic inscriptions were found within the subterranean structure, and these were recorded by Barsanti. Although the sign 𓎛 (ka) appears consistently, the second sign varies in form, making definitive identification impossible.

However, similar inscriptions found on blocks within the stress-relieving chambers of Khufu's pyramid are not royal names per se but crew names. As I noted in Column 5 on page 150, such names may be abbreviated, and therefore not all elements of the original designation are necessarily preserved. Moreover, as seen in the two attested forms of Khufu's birth name—𓅱𓄿𓇋𓄿 and 𓃀𓅱𓄿𓇋𓄿—royal or princely birth names are not always uniform. If an abbreviated form was used, it

would be difficult to infer the full name. It is also entirely possible that ordinary crew names did not contain the sign at all.

4. Structural Transformations in the Late Fourth Dynasty

What is crucial here is that the reduction in scale during the reign of Menkaure cannot be explained simply as a "decline in national power." However, if multiple large-scale construction projects were underway simultaneously, it is entirely plausible that labor, building materials, and the bureaucratic apparatus responsible for coordinating them became dispersed. Such dispersion could easily have affected the progress of Menkaure's pyramid and mortuary temple.

Indeed, it may be more appropriate to assume that, even under Menkaure, a strong "inertial momentum" persisted within the Fourth Dynasty toward maintaining the tradition of constructing giant pyramids. This dynamic resembles the earlier "rebound" in which, after Djedefre pursued an independent architectural program at Abu Rawash, Khafre returned to Giza and revived the giant-pyramid tradition.

Even if the concept of a giant pyramid originated with Khafre himself, such a monument could not have been realized without a bureaucratic organization willing and able to support and execute it. A similar "rebound" may well have occurred during Menkaure's reign, and I propose that the enormous platform at Zawiyet el-Aryan may have been the product of this renewed momentum.

If Prince Khuenre—like his grandfather Khafre—expressed an ambition to build a large pyramid, then the bureaucratic group that had previously constructed giant pyramids would naturally have rallied around him, especially if he was regarded as the likely successor. I therefore suggest that Menkaure, at roughly the same time he permitted Shepseskaf to build a large mastaba, also granted Khuenre permission to begin constructing a pyramid. The officials experienced in giant-pyramid construction may then have mobilized for the project at Zawiyet el-Aryan.

Under such circumstances, laborers, quarrymen, stonecutters,

polishers, and overseers would have been divided among three major projects:
Menkaure's pyramid and mortuary temple,
Shepseskaf's large mastaba, and
the construction at Zawiyet el-Aryan.

For the bureaucratic elite, the project associated with Khuenre—who appeared to embody the future—may have seemed the most attractive.

As a side effect, the pace of construction on Menkaure's pyramid and mortuary temple likely slowed noticeably.

It is plausible that, during Menkaure's lifetime, Shepseskaf—concerned about the delays—took steps, with Menkaure's approval, to accelerate completion:
1. To regard the pyramid as "complete" even without polishing the red-granite casing, focusing instead on finishing the burial chamber and essential internal structures.
2. To dismantle the mud-brick ramps surrounding the pyramid and redirect those resources toward the partially built mortuary temple.

Previously, I accepted the conventional view that Shepseskaf completed the mortuary temple only after Menkaure's death. However, I now consider it more likely that Shepseskaf began this work before Menkaure's death, enabling the complex to be formally handed over to the priesthood and allowing Menkaure's funeral to be conducted properly.

Yet no trace survives of Khuenre contributing to the construction of Menkaure's pyramid or mortuary temple.

From the perspective of Menkaure and Shepseskaf, it must have been evident that one cause of the delays was the diversion of labor and resources to Zawiyet el-Aryan, where many officials had aligned themselves with Khuenre's project.

I do not claim that Khuenre fell from power as a result of conflict with the Menkaure–Shepseskaf faction. But one plausible hypothesis is that Khuenre died suddenly for unknown reasons. If so, construction at Zawiyet el-Aryan would have ceased, the administrative structure centered around him would have rapidly collapsed, and the enormous

trench may have been backfilled with limestone. Notably, Khuenre's tomb in the family cemetery of Menkaure has unfinished wall reliefs, and no sarcophagus is present.

There is no direct evidence to prove this hypothesis. Nevertheless, I believe it offers a coherent explanatory model for understanding three interconnected facts:
Shepseskaf's enormous mastaba,
the unfinished state of the Menkaure complex, and
the massive platform at Zawiyet el-Aryan.

What I emphasize here is not whether Khuenre was truly the owner of the Zawiyet el-Aryan monument. Rather, the key point is that, in the final years of Menkaure's reign, the giant-pyramid construction system that had persisted since the time of Sneferu may have undergone a profound transformation.

The bureaucratic and technical organizations that built the large pyramids of Khufu and Khafre were not mere executors of royal commands; they possessed their own institutional inertia. I propose that this inertia propelled them toward the next giant project at Zawiyet el-Aryan—only for that project to lose its purpose abruptly for reasons unknown.

As a result, during the reign of Shepseskaf, the giant-pyramid system that had existed since Sneferu was dismantled, and by the Fifth Dynasty the underlying values had fundamentally changed. When I look at the unfinished pyramid and mortuary temple of Menkaure, the great mastaba of Shepseskaf, and the immense trench at Zawiyet el-Aryan, it is hard not to feel that the end of the Fourth Dynasty marked a major turning point.

Column 6. Were the Casing Stones Truly Installed All the Way to the Summit?

The Bent Pyramid and the pyramid of King Khafre were clearly covered with casing stones up to their summits, as their present appearance demonstrates. In contrast, most other pyramids—aside from the lower courses where casing stones remain—are almost entirely bare. The six satellite pyramids at Giza are completely stripped, with no fragments of casing stones visible around them. At Dahshur, the Red Pyramid retains casing stones only near its base; according to Stadelmann's study, no upper casing stones have been found.

Pyramids are often described as having been "originally covered to the top with fine white limestone casing, later stripped and reused as building material in Cairo." Certainly, the presence of casing stones at the base of Khufu's pyramid and other large pyramids at Giza confirms that casing work was performed at least on the lower levels. Khafre's pyramid, with casing stones surviving at the summit but largely missing below, is a clear example of substantial removal.

However, I question whether this explanation can be applied uniformly to all pyramids.

First, the presence of casing stones at the base proves only that casing work began—it does not prove that it was completed to the summit. Since casing work proceeds upward from the bottom, surviving lower casing stones indicate the start of the process, not its completion. Even in modern architecture, it is common to finish only the ground level or façade with expensive stone while leaving upper levels or rear sides in simpler finishes. We should therefore be cautious about assuming that lower casing stones imply full casing to the top.

From this perspective, the casing stones of the Bent Pyramid and Khafre's pyramid appear to have served not merely as decorative cladding but as structural elements that restrained the rough core masonry and formed the outer shell of the slope. The exposed core masonry today is

Fig. C6-1. Scattered red granite blocks around the Pyramid of Menkaure (photographed in 2008)

coarse, with uneven faces (Fig. 11-3). In these pyramids, casing stones were indispensable structural components.

By contrast, the Red Pyramid and Khufu's pyramid exhibit a different construction philosophy: relatively well-shaped outer core blocks laid in horizontal courses. In this type, the core masonry itself may have formed much of the pyramid's external geometry. Although lower casing stones were certainly installed, the upper casing stones may not have been structurally essential in the same way as those of the Bent Pyramid or Khafre's pyramid.

The pyramid of King Menkaure is particularly intriguing in this context. Numerous large red-granite blocks—clearly worked stones rather than natural boulders—remain scattered around its base. The use of red-granite casing stones on the lower courses is physically evident.

Yet this raises a question: if later stone-collecting was simply motivated by the desire to obtain valuable building material, why were so many Aswan granite blocks left behind? Granite is hard and difficult to rework or transport, but its rarity and visual prominence make the large quantity

remaining puzzling—especially when contrasted with the near-absence of limestone casing stones supposedly taken from the upper levels. This disparity is difficult to explain through a simple "stone-robbery" hypothesis.

Moreover, even if Cairo required limestone, it seems more rational to quarry fresh stone at Tura and transport it overland than to strip casing stones from the Giza pyramids, haul them down the plateau, and ferry them across the Nile.

By the medieval period, the pyramids were already ancient monuments more than three thousand years old. Their casing stones would have been weathered, sand-covered, and cut to the pyramid's slope—hardly ideal for reuse. Freshly quarried limestone, unweathered and cut to required dimensions, would have been far more practical. Thus, the necessity of removing old casing stones from Giza for construction purposes is questionable.

Of course, we need not deny that some casing stones were reused. Stones that had already collapsed, stones near the base that were easy to remove, and stones from temples, causeways, pavements, and enclosure walls were likely taken. These architectural elements were close to ground level and already shaped for walls or floors, making them far easier to reuse than the sloped casing stones of the pyramid itself.

The explanation that "Cairo's buildings used pyramid casing stones" also faces a quantitative problem. The combined casing stones of the pyramids of Khufu, Khafre, and Menkaure number in the hundreds of thousands. If such a vast quantity had been removed, there must have been a correspondingly massive demand. Yet Cairo today does not contain structures that visibly incorporate such an enormous volume of pyramid limestone. If we adopt the stone-robbery hypothesis, we must ask specifically: where, how much, and in what manner were these stones consumed?

One of the reasons I proposed in Chapter 11 the hypothesis that Khafre's builders may have dismantled and reused portions of Khufu's casing stones—together with the mudbrick ramps surrounding the

monument—was my longstanding doubt that the enormous quantity of Khufu's casing stones can be adequately explained by the conventional view that they were simply reused in Cairo during the medieval period.

The real issue is whether the absence of casing stones today should be immediately interpreted as "the completed casing was later stripped." If casing stones were removed on a large scale, it would have constituted a major demolition project. We would expect to find traces of removal: detachment scars, impact marks, re-cutting traces, accumulations of debris, temporary stockpiles, and transport routes. If large quantities of casing stones had collapsed, unusable fragments and chips should also remain.

In fact, for the Red Pyramid at Dahshur, it seems more plausible that casing stones were reused in nearby Fifth-Dynasty pyramid complexes rather than transported all the way to Cairo. Existing temples, causeways, pavements, and enclosure walls—or collapsed casing stones—would have been convenient sources of material for later construction in the vicinity.

Thus, the question is not "whether reuse occurred," but "what was reused, from where, to where, and in what quantity." Before assuming that upper casing stones were removed wholesale from the pyramid body, we must distinguish between reuse of nearby architectural materials and reuse in distant construction.

I am not asserting here that "the upper casing stones were never installed." Old observation records, surviving stones, scattered fragments, and the condition of the outer core masonry must be examined individually. However, the traditional explanation—that all pyramids were fully cased to the summit and that the missing casing stones were uniformly stripped in later periods—deserves careful reconsideration.

At minimum, discussions of casing-stone loss must examine not only the presence or absence of casing stones but also the physical traces of their removal. The Bent Pyramid and Khafre's pyramid, where casing stones formed a structural outer shell, differ fundamentally from the Red Pyramid and Khufu's pyramid, where shaped outer core blocks were laid horizontally. The meaning of upper casing stones may have varied

between these types.

In the future, if possible, I hope that detailed on-site investigations will be conducted for each pyramid to determine how high the casing stones were actually installed and what evidence exists—if any—of large-scale stone-removal operations.

CONCLUSION

Over the course of writing this book, my perspective underwent a fundamental transformation. At the outset, I focused primarily on the structural characteristics of individual pyramids. Yet only a few weeks into the project, I was confronted by a simple but decisive realization: Khufu's pyramid consists of roughly 2.3 million stone blocks; the essential question is not how a single block was produced, but how millions were quarried, shaped, transported, and assembled.

This insight shifted the entire framework of my inquiry. From that moment onward, my criterion for evaluating construction methods was no longer whether they were theoretically possible, but whether they could sustain the necessary throughput over extended periods.

Part I of this book therefore explores hypotheses grounded in throughput, sustainability, and the practical accessibility of materials in ancient Egypt. These hypotheses are not definitive conclusions; they are attempts—necessarily imperfect—to reconstruct ancient engineering practices through the lens of a modern engineer. My knowledge is not universal, and many ideas presented here remain the conjectures of an amateur.

One episode during the writing process illustrates this clearly. Possessing almost no prior knowledge of stone fracture techniques, I consulted a professional experienced in splitting garden stones. I learned that drilling a series of holes is far easier and more effective than cutting a continuous groove. Further investigation suggested that even a wooden drill shaft, when used with quartz sand, could theoretically bore holes into limestone. Yet when I attempted this myself, the experiment failed. Although the wood-and-sand combination did abrade the stone, the efficiency was far too low. This experience reminded me that engineering reality often diverges sharply from the tidy logic of theoretical reasoning.

In my former work in design and management at Panasonic, I routinely sought advice from other departments, research laboratories, partner companies, and external specialists. Expertise is most effectively obtained from those who possess it. In contrast, while writing this book, opportunities to draw upon external knowledge were limited—a fact I regret. Throughout fields such as construction, civil engineering, production technology, project management, process design, logistics, heavy-object transport, and stone processing, I often felt that true specialists could surely conceive of better methods than those I propose here.

For that reason, this book should be understood as a collection of engineering-based hypotheses about ancient Egyptian civilization. Rather than asserting definitive conclusions, I have sought to imagine concretely what ancient work sites might have looked like and to examine the feasibility of those imagined scenes. If any readers possess practical experience in construction, civil engineering, production technology, project management, process design, logistics, heavy-object transport, or stone processing, I would be grateful if you would evaluate the content from your own professional perspective and consider possible improvements or alternatives.

If, for example, a cross-disciplinary group at a comprehensive university were to bring together specialists from different fields, I believe we could come even closer to understanding the true nature of the massive construction projects undertaken 4,500 years ago. The pyramids were not merely monuments; they were the products of vast, coordinated engineering systems. To approach their reality, we must combine imagination with technical rigor—and remain open to the insights of those whose expertise exceeds our own.

BIBLIOGRAPHY

Primary Egyptological Sources

Petrie, W. M. Flinders. The Pyramids and Temples of Gizeh. London: Field & Tuer, 1883.

Petrie, W. M. Flinders. Medum. London: David Nutt, 1892.

Vyse, Howard. Operations Carried on at the Pyramids of Gizeh in 1837. London, 1840–1842.

Perring, John Shae. The Pyramids of Gizeh. London, 1839–1842.

Maragioglio, Vito, and Celeste Rinaldi. L'Architettura delle Piramidi Menfite. 7 vols. Rapallo, 1965–1977.

Belzoni, Giovanni Battista. Narrative of the Operations and Recent Discoveries Within the Pyramids, Temples, Tombs, and Excavations in Egypt and Nubia. London, 1820.

Möller, Georg. Hieratische Paläographie. Band I–III. Leipzig: Hinrichs, 1909–1936.

Edgar, John, and Morton Edgar. The Great Pyramid Passages and Chambers. 1910.

Faulkner, Raymond O. A Concise Dictionary of Middle Egyptian. Oxford: Griffith Institute, 1962.

Barsanti, Alessandro. "Fouilles de Zaouiet El-Aryan." Annales du Service des Antiquités de l'Égypte, Vols. 7 & 12, Cairo, 1906–1912.

Gardiner, Alan H. "Regnal Years and Civil Calendar in Pharaonic Egypt." The Journal of Egyptian Archaeology 31 (1945): 11–28.

Smith, William Stevenson. "Inscriptional Evidence for the History of the Fourth Dynasty." Journal of Near Eastern Studies 11, no. 2 (1952): 113–128.

Archaeological Reports & Recent Research

Tallet, Pierre, and Gregory Marouard. Le Journal de Merer (Papyrus Jarf A et B). Cairo: IFAO, 2017.

Valloggia, Michel. "Le complexe funéraire de Rêdjédef à Abou-Rawash :

état des travaux après dix campagnes (1995–2004)." Bulletin de la Société française d'égyptologie, no. 161 (2004): 12–27.

Younes, Gamal, et al. "The Pyramid Builders' Waterways: Reconstructing the Ancient Topography of Khufu's Pharaonic Harbour at Giza, Egypt." Journal of Archaeological Science: Reports, 2024.

Stadelmann, Rainer. "Beiträge zur Geschichte des Alten Reiches: Die Länge der Regierung des Snofru." Mitteilungen des Deutschen Archäologischen Instituts Kairo (MDAIK) 43 (1987): 229–240.

Hemeda, S., and A. Sonbol. "Sustainability Problems of the Giza Pyramids." Heritage Science 8 (2020).

Digital Giza. "Khuenre (MQ 1)." Giza Archives, Harvard University–Museum of Fine Arts Expedition.

Classical Illustration Sources

Lepsius, Karl Richard. Denkmäler aus Aegypten und Aethiopien. 1849–1859. Public Domain Mark 1.0, via Internet Archive.

New York Public Library Digital Collections. "Transport of a Colossus, from a Tomb at El Bersheh." 1881–1882.

Metropolitan Museum of Art. Accession Number 26.3.308—Wooden Roller (Middle Kingdom).

Metropolitan Museum of Art. Object Number 31.6.29—Bow Drill Scene from the Tomb of Rekhmire.

Matson Photograph Collection, Library of Congress.

Modern Engineering / Material Science References

Keramat Jahromi, M., A. Jafari, S. S. Mohtasebi, and S. Rafiee. "Engineering Properties of Date Palm Trunk Applicable in Designing a Climber Machine." Agricultural Engineering International: CIGR Ejournal, Manuscript FP 08 002, Vol. X (March 2008).

Geospatial Information Authority of Japan (GSI Maps).

General Works on Ancient Egyptian Technology

Lehner, Mark. The Complete Pyramids. London: Thames & Hudson, 1997.

Arnold, Dieter. Building in Egypt: Pharaonic Stone Masonry. Oxford: Oxford University Press, 1991.

Stocks, Denys A. Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt. London: Routledge, 2003.
Hawass, Zahi. "The Secret Five Chambers." Dig's Days, Guardian's Egypt (guardians.net). Accessed 2026. https://guardians.net/hawass/articles/secretchambers.htm
Dormion, Gilles. La chambre de Chéops. 2004.
Mendelssohn, Kurt. The Riddle of the Pyramids. London, 1974.

General Works on Ancient Egyptian History

Shaw, Ian, ed. The Oxford History of Ancient Egypt. Oxford: Oxford University Press, 2000.
Baines, John, and Jaromír Málek. Atlas of Ancient Egypt. New York: Facts on File Publications, 1980.

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Prince Khuenre as a scribe. Museum of Fine Arts, Boston, Accession no. 13.3140. Harvard University–Boston Museum of Fine Arts Expedition. Photograph © 2026 Museum of Fine Arts, Boston. Used under Media License #26-53829-CC.
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This book reexamines the major pyramid projects of ancient Egypt through the lens of structural development and the evolving technical decisions that shaped them. It challenges the familiar notion that the Fourth Dynasty pyramids represent a simple, linear march toward perfection. Instead, it argues that their history is defined by a far more intricate and irregular trajectory—one marked by experimentation, abrupt shifts, and pragmatic responses to failure.

Each pyramid embodies a distinct set of design choices, construction methods, and engineering challenges. Far from being isolated achievements, they form part of a dynamic sequence in which builders continually revised their assumptions, corrected earlier misjudgments, and adapted to unforeseen structural problems. What emerges is a non-linear pattern of evolution: a record of bold attempts, course corrections, and accumulated experience.

By focusing on design logic, construction technology, and the physical traces preserved in the masonry, this book examines well-known architectural features alongside long-standing "mysteries" rarely evaluated from a practical standpoint—most notably how the builders achieved the throughput required to produce, transport, and install 2.3 million blocks, and how the sustainability of such operations was maintained throughout the project. Hypotheses are tested, refined, and at times discarded as new evidence and structural insights emerge. It is written for readers interested in ancient engineering, construction history, and the technical interpretation of archaeological remains.

ISBN 978-4-911207-90-1

9 784911 207901 >

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Yokohama, Japan